Energy Saving Potential in Hot and Dry Climate by Adjusting Building Fabrications and Application of Dew Point Cooler

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ABSTRACT

This research is to tackle the electricity crises in Kurdistan, as a primary objective, and minimize emissions and global warming effects; this research investigates the potential for the reduction of energy consumption through the use of advanced cooling systems of residential buildings in Kurdistan (Northern Iraq). The objectives are achieved by applying a set of building interventions to existing building fabrications to act as a guide for new residential buildings, and by replacing conventional split air conditioners with newly developed indirect evaporative dew point air-conditioning systems.

A review of residential buildings and their energy-related parameters, and the conventional cooling systems commonly used in hot and dry climates was conducted, in particular, the split air-conditioner. Two different residential buildings, a house and a low-rise multi-flat building, were selected as case studies in Erbil, the capital city of Kurdistan. A critical review of the case studies is presented covering the state of the area, climate conditions, energy and water demands, change in building typologies over time, and most prevalent cooling systems.

The required cooling loads are the core of the research as the ultimate aim is to minimize the cooling load by detailing the optimum building fabrication, then choosing an efficient air conditioning system. The cooling load was investigated and calculated by using realistic occupancy-based cooling schedules and two software (DesignBuilder and EnergyPlus). The procedure included modelling the case study buildings with the DesignBuilder based on the building data from the contractors, followed by transferring the baseline model to the EnergyPlus for further and faster dynamic simulation purposes, then calculating the hourly cooling load for the case studies in Erbil. The most effective and optimum building parameters were identified.

To gain further energy savings, the conventional widespread split air conditioner was replaced with the new dew point evaporative air-conditioner that is more efficient in hot and dry climate such as Erbil. A MATLAB simulation model was used to predict the feasibility of the use of such systems in Erbil's climate. The simulated model was optimized to determine a suitable size and the water consumption of the system. The simulation shows that the energy consumption due to the cooling systems represents 78-79% of all energy consumed in residential buildings and that the hollow clay blocks and a suspended ceiling each allow for a considerable reduction in cooling load. Three centimetres of insulation represents the optimum thickness in terms of the balance between the cost of the insulation with increasing thickness and energy savings. The percentage of energy saving that could be achieved by adjusting the building fabrication could reach 26.8% and combining this with the dew point system yields savings of up to 90.8%. These high energy savings reflect the effectiveness of the new dew point cooler.

An economic analysis was undertaken to verify and calculate the energy savings that could be achieved by adjusting the buildings and replacing the conventional split air-conditioner with the dew point cooling system. By replacing the conventional split air conditioner with the dew point cooler, the base models were found to have a Pay Back Time (PBT) that could be as low as 2.4 years. The environmental effects of the changes were analysed in term of reductions in annual CO_2 emissions, it could be reduced up to 7.2 tons. With the newly developed dew point evaporative cooler, the supply temperature could be lowered to near the inlet air dew point temperature by 65-70%.

A model of the dew point cooler was developed based on the building's cooling load for the sizing purposes, and the effect of building fabrics on the sizing of the dew point heat exchanger per conditioned floor area was determined. It is also predicting the energy and water consumption per floor area of any building in arid climate for both conventional and dew point air conditioner with the effects of the building fabrics. Estimation of energy savings and CO_2 production was given. The figure could be used by the decision-makers in local government to update the current building code based on the results presented for the future buildings and retrofit the existing buildings. In addition, it could be used as a reference for other climate applications as a function of building cooling load.

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PUBLICATIONS

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3-Duan Zhiyin, Zhan Changlong, Zhang Xingxing, Mahmud Mustafa, Zhao Xudong, Alimohammadisagvand Behrang, Hasan Ala. (Indirect evaporative cooling: Past, present and future potentials). Renew. Sustain. Energy Rev., vol. 16, no. 9, pp. 6823–6850, 2012.

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ABBREVIATION:

ASHRAE	*American Society of Heating, Refrigeration and Air-Conditioning*
ACH	*Air Change per Hour*
CO_2	*Carbon dioxide*
COP	*Coefficient Of Performance*
CFC	*Chlorofluorocarbon*
CFD	*Computational fluid dynamics*
CLTD	*Cooling Load Temperature Difference*
Clo	*Clothing*
DB	*Dry-Bulb temperature* ^0C
DX	*Direct expansion system*
DEC	*Direct evaporative cooling systems*
DP	*Dew-Point*
$ECER$	*Evaporative Cooler Efficiency Ratio*
EER	*Energy Efficiency Ratio*
GHG	*Green House Gas*
HMX	*Heat and mass exchanger*
HB	*Heat balance*

HVAC	*Heating, Ventilation and Air Conditioning*
IAQ	*Indoor Air Quality*
IDEC	*Indirect Evaporative Cooling system*
MET	*Metabolic rate*
M-cycle	*Maisotsenko-cycle*
NTU	*Number of transfer unit*
Occ	*Occupancy*
Opt	*Optimum*
PBT	*Payback time*
RTU	*Rooftop unit*
REC	*Regenerative indirect evaporative cooler*
RTS	*Radiant time series*
RH	*Air humidity*
SHGC	*Solar heat gain coefficient*
TFM	*Transfer function method*
USA	*United states of America*
U-value	*Heat transfer coefficient*
WB	*Wet-Bulb temperature ^{0}C*

NOMENCLATURES:

α	*Wall thickness, mm*
$\boldsymbol{a}$	*the temperature and enthalpy saturation line J/kg.K*
$\boldsymbol{Capital\ cost}_{\boldsymbol{dew}}$	*Dew point system capital cost*
$\boldsymbol{Capital\ cost}_{\boldsymbol{split}}$	*Split air conditioner capital cost*
$\boldsymbol{C_{p,air}}$	*Specific heat capacity of air, kJ/kg.K*
$\boldsymbol{C_{min}}$	*the function of the lower heat capacity rates of cold and hot air min(C_{cold}, C_{hot})*
$\boldsymbol{Cr}$	$ratio\ of\ C_{min}\ to\ C_{max} = \frac{C_{min}}{C_{max}}$
DBT	*Dry bulb temperature ^{0}C*
$\boldsymbol{Dew}_{\boldsymbol{maintenance}}$	*Dew point air conditioner annual maintenance cost*
$\boldsymbol{\varepsilon_{wb}}$	*Wet bulb effectiveness %*
$\boldsymbol{\varepsilon_{dp}}$	*Dew point effectiveness %*
Є - NTU	*Epsilon – Number of Thermal Units*
Є	*The effectiveness, epsilon %*
$\boldsymbol{h_s}(\boldsymbol{T_i})$	*inlet air saturation enethalpy in the dry channel*
$\boldsymbol{h_s}(\boldsymbol{T_o})$	*outlet air saturation enethalpy in the dry temperature*
$\boldsymbol{i_{db,r}}$	*Specific enthalpy of air in room temperature, kJ/kg*

$i_{db,2}$	*Specific enthalpy of supply air, kJ/kg*
K	*Wall conductivity W/m.K*
kWh	*kilowatt-hour*
L	*Chanel Length, m*
Low E	*Low emissivity glazing*
M^*	$the\ modified\ mass\ flow\ rate\ in\ the\ dry\ channel$
M°	*Mass flow rate in the channel kg/sec*
N_{ch}	*No of channels*
$Q_{cooling,}$	*Cooling capacity of evaporative cooler, W*
Q_{max}	*Maximum possible heat transfer rate, W*
ρ	*Density of air, kg/m*^{3}
$\rho_{w,f}$	*Secondary air density, kg/m*^{3}
ρ_w	*Water film density, kg/m*^{3}
R	*Material resistivity*
$Split_{electricity}$	*Electricity consumption cost*
$Split_{maintenance}$	*Split air conditioner annual maintenance cost*
$t_{db,1}$	*Intake primary air dry bulb temperature, °C*

$t_{wb,1}$	*Intake secondary air wet bulb temperature, ^oC*
$t_{db,2}$	*Product air dry bulb temperature, ^oC*
$t_{dp,1}$	*Intake primary air dew point temperature, ^oC*
$t_{db,r}$	*Reference dry-bulb temperature of room,*
$t_{db,2}$	*Dry-bulb temperature of supply air, ^oC*
T_{in}	*Cold air temperature ^oC*
T_{out}	*Air temperature ^oC*
$T_{db,in}$	*Dry-bulb temperature of intake air, ^oC*
$T_{db,out}$	*Dry-bulb temperature of supply air, ^oC*
T_i	*Wet channel inlet air temperature ^oC*
T_o	$channel\ exit\ air\ temperature$ ^oC
T_{rad}	*Mean radiant temperature ^oC*
T_{air}	*Air temperature ^oC*
TO	*Operative temperature ^oC*
ton	*A ton is the cooling unit of an air conditioning system. One ton is equal to 3.51 kW.*
U	*Total heat transfer coefficient of the wall between wet and dry channel W/m^2.K*
V	*Velocity m/s*

V_2	*Airflow rate of supply air, m^3/h*
V_w	*Water evaporation rate, litre/h*
V_3	*Secondary air flow rate, m^3/h*
w_1	*Inlet moisture content of secondary air, kg/kg (dry air)*
w_3	*Outlet moisture content of secondary air, kg/kg (dry air)*

Chapter 1: Introduction

1.1 Background

Extensive fossil fuel consumption as a result of human actions has led to increased greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2), ozone, methane and nitrous oxide, and, consequently, serious environmental problems including climate change. Human activities have caused the temperature of the Earth to rise by 1 °C since the 19th century [1]. According to the World Meteorological Organization, the hottest year on record was 2017, and 2016 the most recent year of complete data, was a record year for high carbon emissions. Given the USA withdrawal from the Paris Climate Agreement 2015 and Germany has not been reaching its targets [2]. It is unlikely that the objective of Paris Agreement to keep global average temperatures to within 1.5 °C above pre-industrial levels will be met [3]. This is because of non-legally binding agreement between the countries and have never been any caps on any countries' emissions relating to a global target for emissions reduction.

In the 21st century, more significantly extreme temperatures, dry spells, and precipitations are expected. Cold extremes decline and warm extremes will upsurge in a warmer world [4]. As the hot extremes increase, a cooling system is no longer a needless luxury for cold climate countries. Consequently, the demand for interior cooling is set to grow in the next decades. Hot areas across the world, such as Africa, the Middle East, and some North American states, achieve new high-temperature records every year. Accordingly, the global air conditioning market is growing continuously, as shown in Figure 1-1.

Figure 1-1: Global air conditioning market growth [5]

The Global Status Report stated that buildings and construction are responsible for 39% of energy-related CO_2 emissions: 28% come from energy consumption in buildings and a further 11% from the construction industry. Outputs from buildings and construction contributed to a rise in emissions of almost 1% per year between 2010 and 2016 [6]. In hot climates, the energy used in buildings is high due to the cooling systems that are in operation for long periods of the year. In countries in the Middle East, the energy used for cooling buildings is 50% of the household energy use, as shown in Figure 1-2.

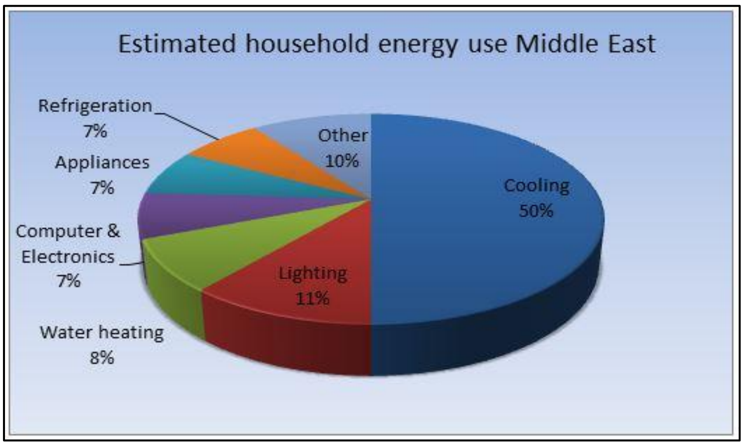


Figure 1-2: Household energy consumption in the Middle East [7]

One example of a hot and dry climate is the Kingdom of Saudi Arabia. Because of a rapidly escalating population and a high level of economic growth, the country is experiencing vigorous infrastructure expansion, especially concerning residential buildings. As a result, the energy demand for residential buildings is at a very high level. The buildings represent 78% of overall energy use in the Kingdom, with residential buildings using 51.2%, as shown in Figure 1-3. Nearly 70% of household electricity is used for air conditioning systems alone for interior cooling during the year because of the hot climate, so air conditioning consumes the majority of the overall energy consumption in the Kingdom of Saudi Arabia [8].

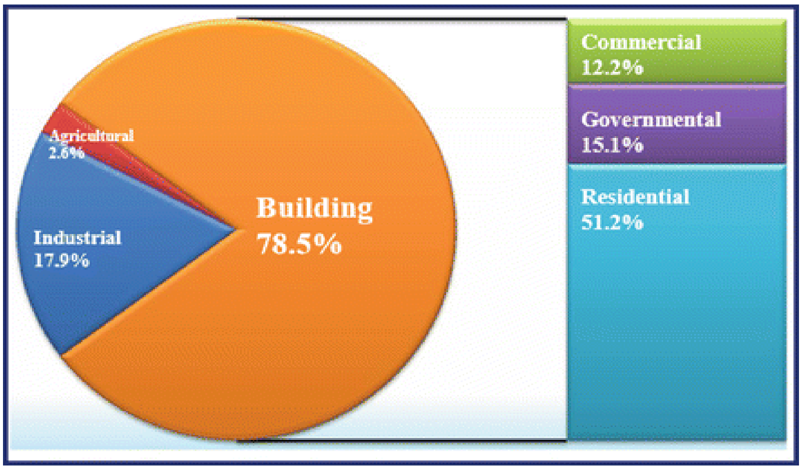


Figure 1-3: Energy consumption in Saudi Arabia by sector [8]

This study focuses on an understudied region of the Middle East: Iraqi Kurdistan. Household energy demand is very high in Kurdistan and covers 54% of overall household energy use, as shown in Figure 1-4, with the largest portion going to air conditioning systems.

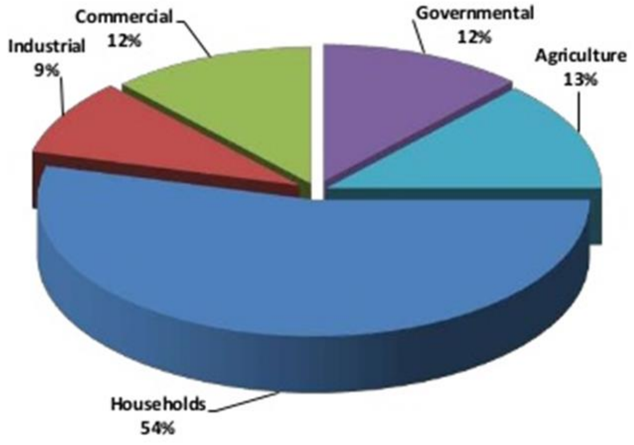


Figure 1-4: Energy demand in Kurdistan by sector [9]

As living standards increase, it is expected that space cooling will grow by more than 80% in developing countries, thus raising the energy demand in these regions. Priority should be given to the building design and materials for new buildings towards eliminating the cooling load of air conditioning. In some climates, natural and night-time ventilation could be utilised for reducing the cooling load [10].

The energy used in cooling could be reduced by 59% in the Saudi Arabian climate simply by selecting appropriate construction fabrication for thermal insulation and external walls [11]. Cooling energy could be reduced by over 30% in residential buildings in the same climate by adopting an appropriate construction type and adding polyurethane thermal insulation to the external walls [8]. In Jordan, the energy requirement for cooling in residential buildings decreased by 40% by insulating walls and ceilings [12]. The annual energy saving in cooling is predicted to reach 73% in Iraq using the high reflective roof in houses [13].

Having a proper building code, which is a set of guidelines that specify the standards for constructed objects for each country's climate, is vital and plays a positive role in the energy consumption of buildings. In 2013, the Emirate of Abu Dhabi established an Energy Conservation Code, based on the 2009 International Energy Conservation Code. The Abu Dhabi building codes were established to meet the needs of the community in the emirate by a set of regulations that would protect public safety and health [14]. The old version of the building code, which was developed in 1983, was revised in 2010 with the intention of providing 23% building energy savings in Kuwait [15].

In parallel with building fabrication and design, the type and efficiency of the chosen air conditioning system have a major effect on energy consumption. Several factors, such as climatic conditions, initial and capital costs, expected thermal comfort, the application of the building and the availability of energy sources, should be considered in order to design and select appropriate energy-efficient cooling systems [16]. Some cooling systems are very effective but have a low coefficient of performance (COP) and are accompanied by high-energy consumption, which has a negative effect on climate change. Direct evaporative cooling systems are economical but not suitable for humid climates, as they introduce droplets of water into the conditioned space.

By replacing a traditional cooling system with a newly developed dew point indirect evaporative one, an energy saving of 87.7-91.6% could be achieved in 10 cities each with different climates, noting that the energy-saving varies depending on the climate [17]. The annual energy saving of a Coolerado (an indirect dew point evaporative cooler) was estimated to be 63% in comparison with a packaged rooftop unit (RTU) and the estimated payback was 7.62 to 41.8 years, according to the facility in which the cooler was installed, while the maintenance cost was almost the same as that of the RTU package [18].

Incorporating a counter-flow regenerative indirect evaporative cooler (REC) into a mechanical air conditioning system can lead to an annual energy consumption saving of 13-58% for different climate conditions [19]. An indirect-direct evaporative cooling system is considered a good choice for residential buildings as it has the following advantages: i) being more energy-efficient; ii) using chlorofluorocarbon (CFC)-free cooling, which is free from environmentally harmful products. It takes advantage of the high heat capacity of water as a cooling medium, so the cooler produces extremely low carbon emissions; iii) consuming less water, as it can save approximately 50% of water in comparison with a direct evaporative cooling system; and iv) the system has a very low initial cost [20].

1.2 Research Problem and Question

Kurdistan suffers from the lack of electricity supply and frequent power cut, especially in recent years due to the rapid expansion in the building sector and population, especially in Erbil. The problem deepens in the summer season because of the air conditioning requirement, as the area is hot and dry. The power cut represents the main issue. The building fabrication is considered one of the key factors that affect the energy consumption in cooling, as the used fabrications have high U-values (W/m^2.K) due to the construction assembly and materials. The absence of proper building code and the inefficient usage of cooling systems is another key factor of the energy problem. There is an absence of researches and investigations on the building materials and their effect on the energy saving to be considered as a standard for buildings in Kurdistan, and the lack of restrictions from the government for the new building resulted in wasting energy at the time that the area suffers from energy production and supply crises. In hot climates, usually, the highest portion of energy consumption is by the cooling systems, using conventional coolers affects negatively on the energy sector. Replacing the old coolers with a more efficient system is necessary to overcome the energy problem. Therefore, the thesis question is; "*how to reduce the energy consumption in the typical residential buildings to minimize the risk of power cuts and keep the comfort level of the occupants intact"?*

1.3 Research Aim and Objectives

As a result of the significant expansion and development in the construction sector, especially in residential buildings in the Kurdistan region, research projects need to be carried out in parallel with the ongoing increase in energy consumption to limit energy usage. In the last few years, the region has suffered from financial crises, increased energy demand with a lack of power resources, as well as a limited amount of research in the power sector. Thus, this research aims to investigate the feasibility of limiting energy consumption by design adjustment of the residential buildings and replacing the older commonly used air conditioning coolers with a newly developed dew point indirect evaporation cooler. To achieve this aim, this research sets five objectives:

1. To undertake a wide review of the literature on buildings in hot and dry climates in terms of building fabrication and codes. Besides, to conduct an intensive investigation of the cooling systems used in these types of climate, concentrating on indirect evaporative dew point cooling systems, as there are challenges faced in their application due to the novelty of the system.

2. To identify typical residential buildings representing housing stock in Erbil governorate located 36.2 latitude (N) and 44 longitude (E) and enable to collect the data for the dynamic thermal simulation, and to recognise a set of interventions to improve the performance of the residential buildings.

3. To extract secondary data from the case study buildings for conducting a dynamic thermal simulation using suitable software, then determine the cooling load for the base and adjusted cases in terms of the optimum fabrication for buildings.

4. To simulate and optimize a new dew point cooling system to identify the optimum size and water consumption of the new cooler, and to provide guidelines to the households and designers in terms of the unit size, as well as water and energy consumption.

5. To analyse and compare the annual water and energy consumption in the cooling applications of the case study buildings, for both conventional split and novel dew point cooling systems. As well as the economic analysis and environmental effect of both case studies, then calculate the economic and environmental benefits for a larger scale covering all investment projects in Erbil.

1.4 Research Methodology

The overall design of the research is illustrated in Figure 1-5. The literature review explores the buildings in terms of typology, fabrications, and design in hot and dry climates. It illustrates the conventional cooling systems, as well as the newly developed dew point cooler. Then the study context clarifies the circumstances of the area and the related issues. Consequently, the research gap and problem will be identified. To solve the problem of the research, the case studies need to be chosen, as secondary data to represent the typical building models in the area, details of geometrical dimensions and building fabrication are necessary for further investigations in the study.

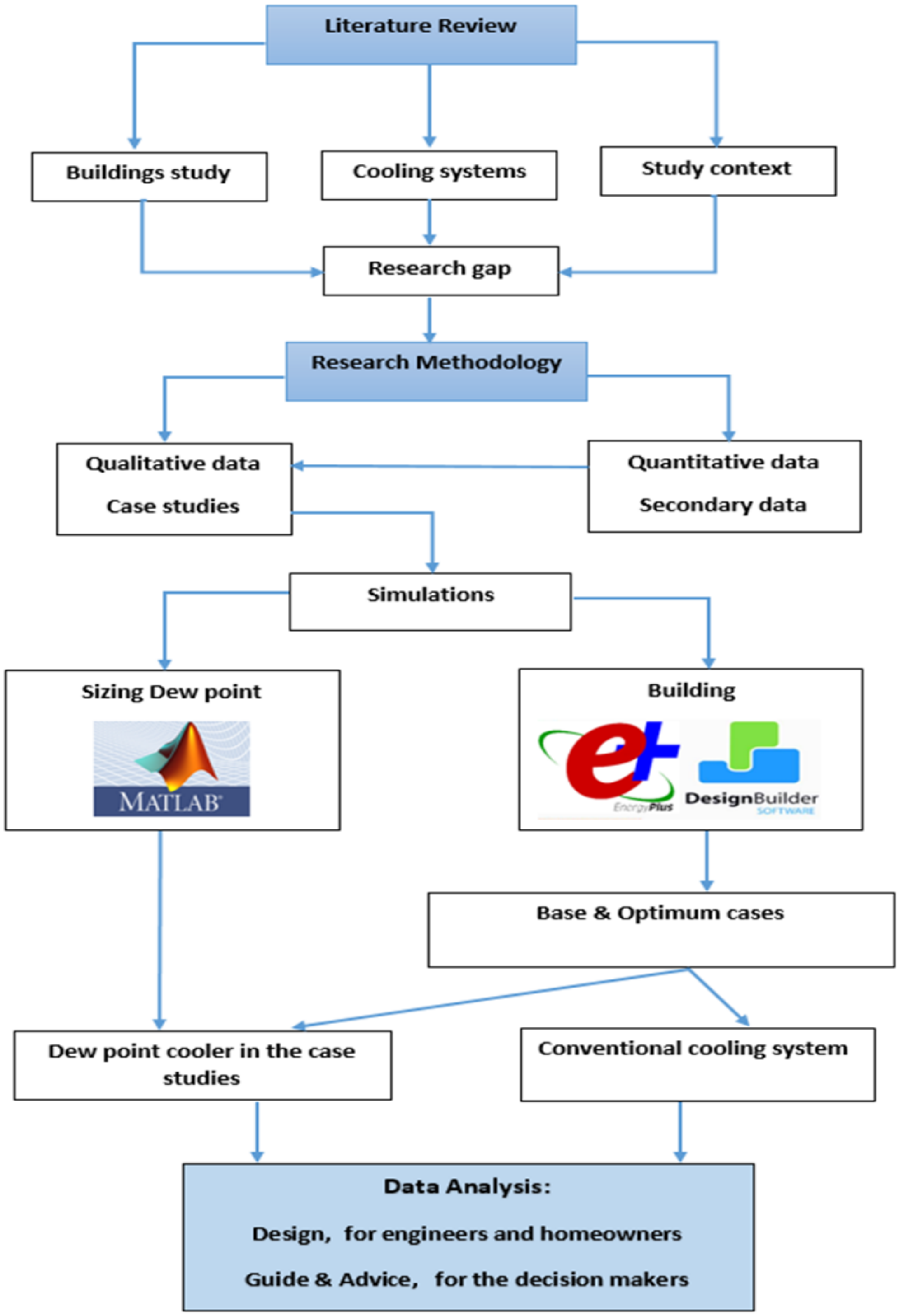


Figure 1-5: the overall design of the research

The study includes a review of the relevant literature to observe buildings in hot and dry climates, their building materials, codes, and applicable air conditioning systems. The study also investigates a new dew point cooling system. The investigations in the literature review enabled and simplified the implementation of the main approaches used in the study. An outline of the steps of the methodology are shown in Figure 1-6

Objective 1 & 2

Literature review (chapter 2) & Context and case studies (chapter 3)

* Reviewing and investigating the common cooling systems.
* Reviewing building parameters.
* Identifying the typical case studies.

Objective 3:

Cooling load (chapter 4)

* Designing case study models, using DesignBuilder software.
* Simulating and transfer models to energy plus.
* Calculating the cooling load for both case studies.
* Evaluating the effect of parameters on energy and cooling load, using EnergyPlus and selecting the optimum parameters for the case study models.

&

Objective 4:

Dew point cooling design (chapter 5)

* Simulating dynamic model of cooler by MATLAB.
* Optimization of the designed cooling unit and combining it with selected case studies.
* Finding the best size and water consumption for the cases.

Objective 5:

Economic and environmental analysis (chapter 6)

* Calculating annual energy saving, the payback time of both case studies.
* Calculating the annual CO_2 reduction of both case studies.
* Calculating economic and environmental benefits for a larger scale covering all investment projects in Erbil.

Figure 1-6: Schematic diagram of the study approaches

The approaches employed in the methodology for the study are as follows:

Approach to objectives 1 and 2 - Literature review and case studies selection: This approach identified general information about the buildings and the most widely used cooling systems in hot and dry climates as a basis for further investigation in the study. It was also intended more specifically to identify two different building typologies in a city with a hot and dry climate. The approach was also used to i) investigate the city in terms of climate, energy resources, and consumption as an illustration of its development and importance, and the reason for nominating the city for study; and ii) demonstrate building typologies, fabrications, design, and codes. Details of the case study city and buildings are presented in **Chapters 2 and 3.**

Approach to objective 3 - Cooling load of selected residential buildings: This approach was used to estimate the cooling load of both case study buildings**,** including i) annual weather data extracted from relevant sources; ii) using the secondary data collected from an actual residential project, then preparing a model of each case study building using appropriate software; iii) using personal knowledge of Kurdish life style and communication but not formal survey for assumptions of the operating schedules. Ethics approval has been obtained prior commencing the work, and it was considered as a low risk.; iv)calculating the cooling load of the base case for both buildings, and v) finding the optimum parameters of the fabrications of the buildings. Each step taken in calculating the cooling load is detailed in **Chapter 4**.

Approach to objective 4 - Dew point cooling design and application in the selected buildings: The approach included: i) developing and operating a logical dynamic computer simulation model for a novel dew point cooling system, based on a previously published study, then validating it with published experimental data; ii) optimizing the designed cooling unit using maximum cooling output, minimum water consumption and the geometrical size of the unit, and iii) applying the dew point cooling system to both case studies depending on the cooling load profile from the second approach, to determine the unit size and water consumption and predict the viability of the system in real climate conditions. Details are presented in **Chapter 5**.

Approach to objective 5 - Comparison of conventional and dew point cooling systems: This approach included: i) the application of both split and dew point cooling systems to both case studies and a comparison of their energy and water consumption; and ii) study the economic and environmental analysis of both cooling systems. The approach is detailed in **Chapter 6.**

1.5 Research Limitation

The main issue of the study was the lack of resources and publications about Iraq generally and Kurdistan particularly, as Iraq passed through several wars during the last few decades that isolated it from international connections and researches. Consequently, the research required extra effort and time to overcome the problems.

1.6 Thesis Structure

Chapter 1 – Introduction: This briefly defines the research background, objectives, research concept and methodology.

Chapter 2 – Literature Review: This presents the results of an extensive review of the literature relating to residential buildings, covering building fabrication and cooling-related parameters in hot and dry climates. The review also covers the main cooling systems used in the area and the dew point cooling system, concentrating on the latter as it is new, is still in its improvement stages, and is a popular subject for researchers working in the cooling field.

Chapter 3 – Context and Case Studies: This chapter describes the state of the chosen area in terms of expansion, the extent to which it is booming, energy shortages and climate. The chapter then specifies the case studies and clarifies the reasons for their selection.

Chapter 4 – Cooling Load: This chapter is considered the core of the study, as it presents the calculations of the cooling load for the two case study buildings, using suitable software. This output is the result of a process of identifying building geometries and fabrications, as well as other related parameters, such as occupants and their activities, and cooling time schedules.

Chapter 5 – Dew Point Cooling Design, Sizing and Water Consumption: This chapter includes the simulation, validation, and optimisation of the dew point system applications according to weather data for the application climate. The output is used to predict the water consumption and size of the cooler for both buildings (the case studies), and the simulation demonstrates the viability of the system in the specified climate conditions.

Chapter 6 – Economical and Environmental Analysis: This chapter analyses the application of both systems (the split and dew point air conditioners) and then compares their annual performance, energy payback periods, and carbon emission reductions for the climate in Kurdistan. It addresses the potential feasibility of using dew point cooling systems in comparison with traditional split air conditioners by assessing both the economic and environmental benefits.

Chapter 7 – Conclusion and Further Work: This chapter concludes the main observations and findings from the study. It presents suggestions for the possible adjustments to residential buildings and alternatives to the conventional cooling systems for more energy savings to solve the energy shortage problem in Kurdistan. The chapter also suggests further opportunities for investigations with the same aim.

Chapter 2: Literature review

2.1 Introduction

This chapter presents a detailed review of the literature on residential buildings and the conventional cooling systems commonly used in a hot and dry climate. The main objectives of the chapter are to:

1. Identify and define energy-related building fabrication parameters and analyse their role in saving cooling energy through a critical review.

2. Demonstrate the cooling systems most commonly used in a hot and dry climate and their specifications and to review the research about them.

3. Present the concept behind cooling systems, concentrating on the new dew point cooling technology and the theory behind it, and describe the performance evaluation criteria of the system.

4. Illustrate a detailed review of the dew point cooling system to identify the optimum geometric and operational parameters of the technology.

5. Present a review of data regarding cooling load in residential buildings and the opportunities for decreasing it to reduce the energy consumed in those buildings.

6. Identify the economic and environmental benefits of the energy saving from building fabric intervention and creating more efficient cooling systems in hot climates. A combination of these objectives will identify the gap in knowledge within which this work makes a contribution.

2.2 Residential Buildings

In general, the dominant local climate influences building methods and styles. Consequently, it is logical that building typologies around the world are very different. Factors such as the raw materials available, land prices and general financial status can lead to a diversity of buildings, even in countries with the same or similar climates. Residential buildings are named differently throughout the world but are generally divided into two main types: houses and apartments. In the hot and dry climates of the Middle East, the design and materials of residential buildings differ from those built in the same climate in the USA and depend on the availability and cost of the building materials and the expertise of the workforce.

2.3 Building Envelope Parameters

As well as the building layout, design, geometry, and the building shell parameters affect cooling and heating consumption directly. These parameters comprise external walls, roof doors, window size and placement, glazing and insulation. The choice of material and sizing for these components has a large effect on the heat transfer between the internal and external environments and, therefore, the performance of the building in the weather conditions in the region.

2.3.1 Insulation

Insulation limits heat transfer through the building shell, which directly affects the cooling and heating load in providing comfort for the occupants. The most common building insulations and their properties are shown in Table 2-1.

Table 2-1: Common insulations and their properties [21]

Insulation material	R-value	**Environmentally friendly**	**Flammable**	**Notes**
Fibreglass	R-3.1	Yes	No	Does not absorb water
Mineral wool	R-3.1	Yes	No	Does not melt or support combustion
Cellulose	R-3.7	Yes	Yes	Contains the highest amount of recycled content
Polyurethane foam	R-6.3	No	Yes	Makes a very good sound insulator
Polystyrene (EPS)	R-4	No	Yes	Difficult to use around imperfections

With the aim of reducing the heating and cooling load of buildings in Iraq, Wahib [22] studied experimentally the effect of thin insulation when the temperature rises to 45°C. Baghdad was selected for the test, which ran from 3 May to 4 June in 2015; 1 cm polystyrene insulation covered with aluminium foil was used in the test to cover the test room and partially cover the eastern and southern part of the external walls. The result was a reduction in the load from 4 to 2.4 kW and the annual energy use reduced from 616 to 420 kWh, achieving an energy saving of 65 kWh/m^2/year (30%), as illustrated in Table 2-2.

Table 2-2: Effect of insulation on power and annual energy saving [22]

Power consumption

Description	**Cooling load For room (kW)**	**Annual cooling energy (kWh/m^2 yr)**	**Annual electricity demand (kWh/m^2 yr)**	**Energy saving (kWh/m^2 yr)**	**Indoor temp. (C)**
Without insulation	**4**	**616**	**210**	**-**	**36**
With insulation	**2.8**	**420**	**145**	**65**	**32**

Ozel [23] also studied the location of insulation on external walls and optimized the selection numerically. The city of Elazig in Turkey was chosen for the study, as well as a South-facing orientation. Three locations in the construction were used in the study, as shown in Figure 2-1. The results reported that the optimum insulation thickness was not affected by the location of the insulation in the wall but that the external location of the insulation materials gave the lowest temperature fluctuations.

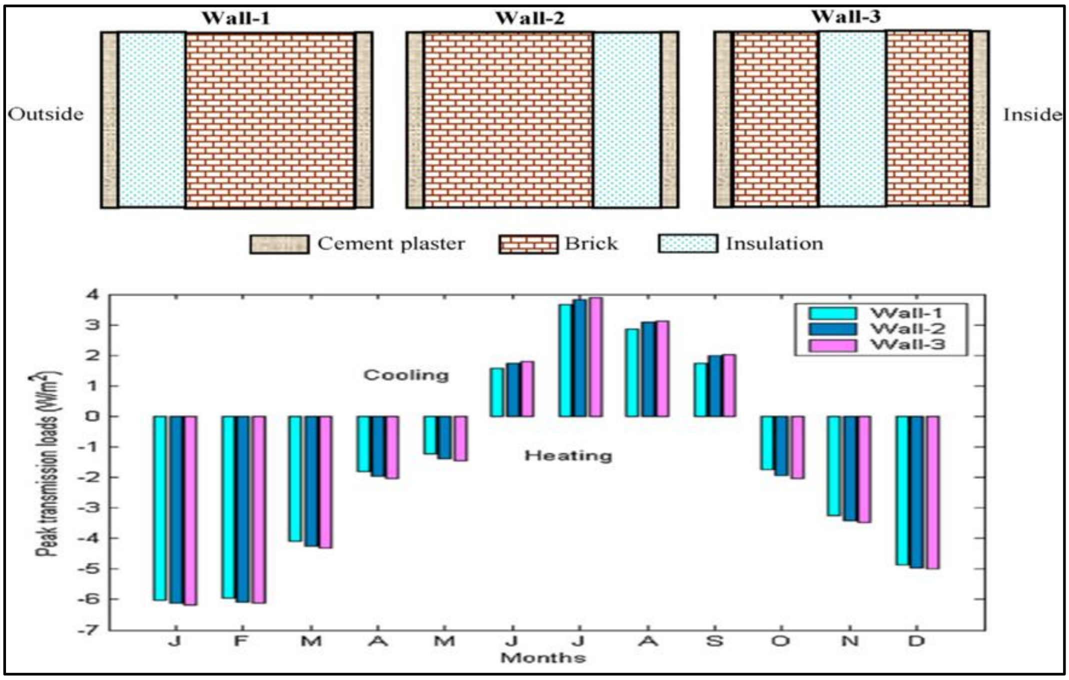


Figure 2-1: External wall insulation location and its effect on cooling load [3]

Friess et al. [24] studied the energy saving in villa residential buildings in the United Arab Emirates (UAE) following government legislation implemented to insulate external walls and roofs. The legislation had been introduced to reduce energy consumption in response to the growth in the number of buildings from 20,000 in the year 2000 to 60,000 villas in 2009 and an energy consumption rise of 300% over nine year period. DesignBuilder software was used in the study; the results showed that simply insulating a building from outside led to up to 30% energy saving. Al-Sallal [25] compared polystyrene and fibreglass insulation materials in a 108 m^2 residential building using

RENCON simulation software to calculate the annual heating and cooling requirements. The study showed the importance of using the life-cycle cost analysis method for the kind of insulation and its thickness in relation to the building. Many cases were studied based on the resistance of the roof insulation (such as R5, R10, R15, R20, R25, and R30). It was concluded that R10 fibreglass was the most cost effective. It was also concluded that spending money to improve the insulation in a house in a cold climate had better yields than for homes in a warm climate.

Bolattürk [26] studied several Turkish cities to identify optimum insulation thickness. External wall insulation was assessed based on annual cooling/heating loads. Using cost-effective methods, the research showed the optimum thickness for each city: Adana 3.2 cm, Aydin 3.3 cm, Hatay 3.4 cm, Iskenderun 3.7 cm, Izmir 3.2, and Mersin 3.4 cm. Daouas [27] studied Tunisian residential building energy consumption and the impact of using insulation materials on roof construction to reduce the thermal conductivity of the roof. Two typical roof constructions were selected for the study, which used the complex finite Fourier transform method to handle the nonlinear longwave radiation exchange with the sky. Annual cooling and heating energy were estimated and used in the life-cycle analysis conducted in the study. Rock wool was used, and the optimum thickness was found to be 7.9 cm with a payback period of around 6.06 years, showing an energy saving of 58.06% in comparison with a roof without insulation. The study emphasized the importance of cost analysis before choosing an optimum thickness of insulation, as increasing the thickness of insulation is sometimes a waste and will have an inverse effect.

In summary, insulation is vital in buildings, as it could save a significant percentage of the energy used for cooling. Polystyrene is one of the most common materials for building insulation. External walls and roofs should be the main target, as simply insulating external walls could save more than 30% of the energy used. The optimum insulation thickness is not affected by the location in the wall, but external insulation is more effective due to less indoor temperature fluctuation and greater stability as the thermal mass is inside rather than outside the insulation layer. Cost should be taken into consideration, as extra thickness does not mean extra energy saving, and each location has its optimum thickness for insulation.

2.3.2 Thermal mass

A building's thermal mass is the construction material's capacity to absorb, store and release heat. For example, using very dense construction materials, such as concrete, concrete blocks, and stone in the buildings increases heat storage capacity due to their high specific heat capacity J/kg.K and of its comparatively high density [28],[29]. Building parts that are made with high thermal mass capacities, such as roofs, external walls, and ceilings, which have direct contact with the internal environment, have a significant impact on the internal conditions and, accordingly, the energy consumption for cooling and heating.

Al-Taie et al. [30] investigated the past and present states of Iraqi building construction and the materials used. Their study covered two styles: the Ottoman era and the time of British occupation. The research showed that building style remained unchanged during the occupancy between 1639-1917 of the Ottoman Empire when citizens depended on mud, clay bricks, clay mixed with hay, or stones for stronger structures, and gypsum. The style changed with the British occupation (1917-1958), when new building materials, such as cement blocks, iron beams, and cement as a binder were used in building construction. The new British Empire style did not consider the harsh weather in Iraq in the summer, but some Iraqi engineers followed and adopted the western British style of construction and materials without consideration of the harsh climatic condition. Mohamed et al. [31] studied the typical roof style of Iraqi residential buildings and the effect of reducing thermal capacity on cooling load as the demand for electricity increased and 42% of the energy consumed by the residential buildings. They added coatings and layers to the roof externally and internally using radiant barriers and found that making those changes to the building would lead to an annual energy saving of 6-17.4%.

Nematchoua et al. [32] examined the external wall thermal mass of Cameroonian residential buildings, as, following an increase in energy use and outdoor temperatures, the country suffered power cuts and could not manage energy demand. The researchers studied the two cities of Yaoundé and Garoua and examined two different block walls: concrete blocks and a compressed stabilised earth block wall. They reported that insulating the external walls would reduce cooling energy consumption. Insulation materials were used to reduce the cooling energy demand with consideration for the orientation of the buildings, and the optimum insulation and orientation were specified. The best case was 8 cm thick polystyrene insulation on the South orientation, which achieved a saving of $ 51.69/m2; the second-best case was 11 cm insulation with a North orientation, which recorded a saving of $ 97.82/m2. The trade-off is between the cost of insulation and savings made. If the insulation is external, the inconvenience of taking space out of the room is not an issue. Further information regarding the output of the study is shown in Table 2-3.

Table 2-3: Optimum insulation on external walls and payback period [30]

Locality	Yaoundé				**Garoua**			
Orientation	**South**	**North**	**East/West**	**CDD**	**South**	**North**	**East/West**	**CDD**
Optimum insulation thickness (m)	0.080	0.07	0.08	0.034	0.12	0.11	0.125	0.0835
Energy savings %	79.87	77.89	79.71	62.24	85.31	84.36	85.65	80.21
Payback period (years)	4.78	5.14	4.63	9.31	3.39	3.69	3.38	4.66

In summary, selecting appropriate materials and fabrics which form building parts is important, especially the external elements. Concrete blocks have a high capacity for absorption and retaining heat. Clay bricks were always used in the past and have largely been replaced by concrete. Roofs have very high thermal capacity because they contain cement and metal meshing. To address the large thermal mass in existing buildings, insulating the structure is the most effective way to reduce and delay the time of heat transmission in the hot climate zones such as Iraq. Using different materials for new-build properties further reduces the heat transfer into the building.

2.3.3 Building U-values

The U-value is the thermal transmittance or heat transfer coefficient of a material or a combination of material layers, such as a wall, and is measured in watts per square metre per degree Kelvin or Celsius ($W/m^2.K$). This value shows the effectiveness of the transfer of heat of construction material or a combination of many materials in one assembled building part. The choice and design of glazing, walls, and roofs are decided by their U-values. In buildings, a lower U-value generally means less energy transferred into/out of the building and less energy is required to maintain comfort. Today, most countries have strict rules for the materials used in buildings, known as building regulations, and the regulations differ from one country to another. For example, in the European Union, the International Organization for Standardization (ISO) sets the regulations [33], while the UK follows British Standards (BS) [34].

Kharseh et al. [35] investigated Middle Eastern residential buildings and selected Qatar as a case study. They studied a single house of 144 m^2 supplied by the Qatar General Electricity and Water Corporation (KAHRAMAA). The U-values of the external walls and windows were reduced to save energy and lessen the cooling load. It was concluded that exchanging the window from single to double glazing significantly lowered the U-value from 5.06 to 3.04 $W/m^2.K$, and reduced the cooling load by 4.5% . A reduction of 28% in cooling load been achieved due to the improvement of external walls U-value from 1.76 to 0.57 $W/m^2{\cdot}K$. Cuckow et al. [36] calculated examples of U-values using a specified method for a large range of building assemblies and combinations of materials. The selection covered timber walls, insulated cavity with metal wall ties, pitched roofs and floors U-values. The U-values for the walls is in the range 0.30-0.32 $W/m^2.K$, for glazing and roofs 0.2-0.32 $W/m^2.K$, and for floors and suspended ground floors were 0.22-0.25

W/m^2.K. The given construction assemblies could be benefited and adopt the used methodology to improve and reduce building U-values.

Suleiman [37] conducted experiments to compare the conductivity (U-value) of traditional North African (Libyan) houses using the local materials available since the 1970s in Benghazi. The rigid construction of these types of houses was based on concrete-backed stone masonry, with limestone bricks joined with mortar, forming the external walls of the building for insulation and to save energy. The U-value of the external wall was found to be 3.03 W/m^2.K for the soft bricks and 5.26 W/m^2.K with hard cement bricks; the ground-floor slabs recorded 1.46 W/m^2.K. Table 2-4 illustrates the U-values of the Libyan building materials.

Table 2-4: U-values of Libyan building materials [37]

The *U*-values of the multi-layered construction elements of the building envelope and the corresponding estimated annual energy consumption E.

Construction element	Effective thickness(m)	R_T (m^2 k/W)	U_T (W/m^2 k)	E (kWh/m^2)
External wall (soft bricks)	0.240	0.33	3.03	40.26
External wall (hard bricks)	0.240	0.19	5.26	69.93
Slab on ground floor	0.345	0.70	1.46	18.98

Friess et al. [24] studied new housing buildings fabrics U-value in the UAE after rapid construction increase in the country, causing a 300% increase in energy demand. The mid-plane blocks insulated for external wall use, it recorded a U-value of 0.57 W/m2.K, when originally was simulated as 2.398 W/m2. K, it was shown that only improving the U-value of the external wall could save 30% of the annual used energy. Ghisi et al. [38] studied the effect of construction on bedrooms in a multi-apartment low-rise residential building in Brazil, their main conclusion was that the outer area and the U-value of the external wall were the largest variables to increase the internal air temperature, and these had to be minimized to improve internal conditions in the summer season. Solar factor is the percentage of solar energy that transmitted indoor through the glass both directly and indirectly, this value is compared to clear 3mm glass which its value known as S.F 0.87, (0.85 directly transmitted and 0.02 indirectly reradiated indoor as gain) while the solar coefficient S.C is the total heat passing through a glazing and is a ratio of solar factor of a particular glazing to the clear 3mm glazing. Nagy et al. [39] studied the impact of shading and glazing combinations in hot and dry climates. The study examined a residential building in Tucson, Arizona, for which the researchers studied the effects of two different forms of glazing: with and without shading. The improvement of solar coefficients for both windows and sliding doors (0.57 and 0.37) and U-values of (1.95 and 1.67) $W/m^2.K$ resulted in a reduction of 0.4 kW in the cooling load, and a daily energy saving of 11-14%.

In summary, the U-value is a physical property of a material and the thermal transmission of that material. In buildings, the U-value could be for one material, such as glazing, or a combination of materials together in one number representing the assembly of several material layers, such as in walls, floors, and roofs. U-values reflect the direct effect on the magnitude of energy transmitted into a building, whereby the smaller the U-value, the better the construction and the more efficient the use of energy. Different countries have different limits for their construction U-values, regardless of the type of assembly. Developed countries set very low U-values due to energy saving challenges. Concrete, stone, and brick have high U-values, while insulation has a very low U-value.

2.3.4 Glazing and Solar Gain Controlling Measures

Glazing and solar gain are considered key parameters that have a significant impact on the cooling load of a building. Having a larger area of glazing in a building means more solar radiation heat gains by transmitting and absorbing, subsequently releasing the heat to the building. This has advantages and disadvantages. For example, this could be beneficial in winter when heating is required but increasing the size of windows has an inverse impact on cooling in the summer due to the high solar heat gains that lead to overheating in the building. The difference in U-values between external walls and glazing to the detriment of the glazing leads to an increase in the total conductivity U-value of the whole building, increasing the heat gain/loss through the envelope. On the other hand, having a larger window size allows more daylight to enter the building, although a large amount of light can reduce visual comfort.

In one study, Alwetaishi [40] considered the impact of the glazing/wall ratio on energy. Five different glazing/wall ratios were studied (5%, 10%, 20%, 30% and 40%) in buildings in Saudi Arabia. Dry/hot, dry/humid and moderate climates in the cities of Abha, Riyadh, and Jeddah were selected for the research. TAS EDSL modelling was used and validated by a monitoring study. The study used questionnaires to collect information about the actual comfort level in the studied cases. It was concluded that East and south building orientations were among the worst in terms of heat gaining and the window/wall ratio should be kept to around 10% for hot/dry and hot/humid climates, but around 20% was recommended for moderate climates. Samaan et al. [41] investigated the optimisation of cooling load in Egyptian university building halls by improving the windows' external shading, using low-transmittance glazing and ventilation systems. The building was improved and showed a reduction in cooling load of 26-31% compared with the base case. Single-, double- and low-emissivity glazing were used in the study. Double glazing alone did not show a significant change, but low-emissivity glazing recorded a reduction of 8-10%. An overhang of a 1.5 m projection with louvres (blades with 0.5 m projection) over the external windows had the maximum effect on cooling load reduction without considering daylight. The study also showed the importance of using building performance and simulation tools in research work.

Lu et al. [42] have modified the solar heat gain coefficient (SHGC) for cooling load calculation purpose in a transparent envelope.They concluded that the modified SHGC is 0.67 for double glazing while the original is 0.71, and the modified SHGC differs with different building construction parameters. Shaik et al. [43] also studied different window shading effects on various forms of single glazing, with and without overhangs. The study took place in India in cities with four different climate conditions: hot/dry, hot/humid, moderate and composite. Bronze glazing window(BGW), clear glazing window(CGW), green glazing window (GGW), grey glazing window(GrGW) and blue-green glazing window(BgGW) were selected in the study, as shown in Figure 2-2. DesignBuilder simulation software was used for the modelling and simulation, several different projections of overhangs were used. It was reported that a grey glass window with a 1.5 m overhang had the optimum result for energy reduction and minimizing the cooling load.

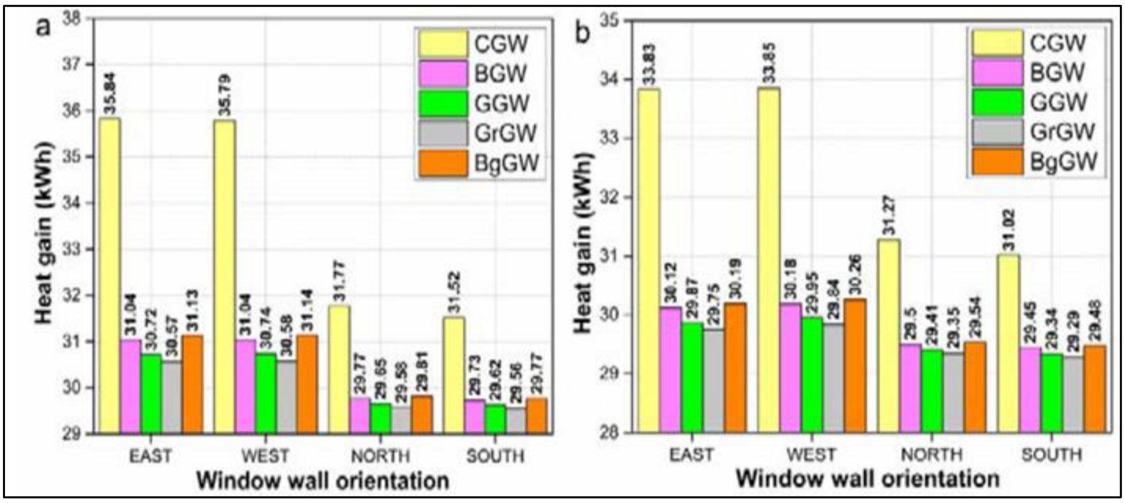


Figure 2-2: Overhang effect on different glazing types and orientations in a hot and dry climate, [43]

Kirankumar et al. [44] also investigated building orientation effect and selected dense concrete and fly ash bricks for comparison in India's climate. It was reported that fly ash blocks with grey glazing and a South orientation had the maximum effect on cooling load and energy conservation, as illustrated in Table 2-5, and a reduction of 21.51 kWh was recorded in the Ahmadabad region of the country.

Table 2-5: Orientation effect on energy consumption in a dry and hot climate in India [44]

Solar heat gain in fly ash brick buildings with different glass materials in four orientations of window glass for Ahmadabad region

Direction (kWh)	Clear glass (kWh)	Bronze glass (kWh)	Grey glass (kWh)	Green glass (kWh)	Blue green (kWh)
East	26.05	22.5	22.26	22.34	22.55
West	25.77	22.31	22.07	22.14	22.36
North	23.32	21.65	21.55	21.58	21.68
South	23.1	21.62	21.51	21.56	21.64

In summary, glazing can have different effects on cooling load and cooling energy: in hot and dry climates, a window/wall ratio of 10% is recommended, and for moderate climates 20% is adequate. Clear double glazing alone does not have much effect on reducing cooling load, whereas low-emissivity glazing with external shading is effective in the reduction of solar heat gain. Orientation also has to be considered when designing windows.

2.3.5 Air Infiltration Rate

Uncontrolled air that flows into a building is called infiltration and can occur through cracks or other openings such as doors or windows. The rate of infiltration depends mainly on indoor and outdoor air temperature difference, pressure, wind direction, and the construction type and quality. This rate is also known as building airtightness or building air leakage. Infiltration in a building causes heat gain in the summer and heat loss in winter, which causes a rise in internal load and energy consumption. According to the American Society of Heating and Air-Conditioning Engineers (ASHRAE), buildings can be divided into three categories: tight, medium and loose or leaky. ASHRAE's [45] advice regarding estimating and calculating infiltration is to take the total infiltration rate for the building, rather than each zone on its own. There are two main factors that affect the rate of infiltration: the first is the effective leakage area (ELA) and the second is the pressure difference caused by buoyancy (the stack effect).

Sherman [46] experimentally studied the infiltration rates in residential buildings based on ASHRAE 62.2 standard. It was stated that in the USA, most houses are naturally ventilated through infiltration caused by air leakage. Newer homes in the Western world are airtight and require mechanical ventilation. In the study, Infiltration efficiency was calculated for six different cities, covering mild, windy, cold, and hot climates. It was reported that the main parameter was the appropriate exposure period. Infiltration could be very effective when long time exposure is relevant. Another study, Van Hoof et al. [47] investigated the thermal comfort in Holland houses found that the rate of infiltration was calculated to be around 0.3 air change rate (air changes per hour, ACH) for a mechanically cooled residential building. Centnerova et al. [48] researched the energy and indoor effect on adaptive thermal comfort in centrally controlled heating, ventilation and air conditioning (HVAC) in the Czech Republic and the Netherlands. However, they did not consider infiltration in the study; natural ventilation is not taken into account as its effect is minor.

Bimaridi et al. [49] investigated the outside air supply and the effect of infiltration in comparison with the ventilation rate. They reported that infiltration could provide enough fresh air to a commercial building if the conditioned space was leaky and, if space was cooled with split systems, the infiltration rate would be very small. Wang [50] specifically described the air infiltration rate and methods of calculation for each parameter and openings. The infiltration rate for a whole house could be around 0.31 ACH and, if the internal doors between zones are open, this rate rises to 0.9 ACH. This rate is also between 0.2-0.3 ACH if the windows are small in a low-rise building. Klevien [51] conducted experiments to study the infiltration rates in two different-sized houses in two seasons, winter and summer. Two houses, of 77 m^2 and 100 m^2, were chosen in the test and a pressurization method using a 1.42 m^3/s fan. The infiltration rate was much higher in winter compared with summer when considering different wind velocities and directions and temperature differences. With different temperatures and an average velocity of 1.3-1.6 m/s, the infiltration rate was 0.07-0.17 ACH for the smaller house and 0.06-0.23 ACH for the larger house. It was confirmed that the infiltration rate calculated in the test was slightly less than the tested experiment readings.

In summary, infiltration rates differ with the season, and this rate is much higher in winter than summer because of the temperature and density difference between indoor and outdoor air. The rate also varies with the type and age of the building. ASHRAE recommends taking one value for the whole building, rather than different values for the separate zones. Infiltration could be enough to replace the ventilation required. A 0.3 ACH is the recommended rate for cooling residential buildings if there is no air leaking to other zones, as higher rates cause a rise in cooling load.

2.4 Building Codes and Regulations

Building codes are sets of regulations, designs, and rules for buildings that deal with welfare and public interest. Building codes deal with the construction and occupancy of buildings and protect the building's form and shape. They have been defined by the Building Officials and Code Administrators (BOCA) in the USA [52] as a set of regulations for protecting public health, welfare, and safety. Each country has its own methods of issuing building codes depending on the purposes and priorities, considering climate conditions. A building code is normally set by a group of researchers from academic institutions and professional members. For example, the International Energy Conservation Code [53] in the USA includes detailed information on the minimum requirements to safeguard public health, general welfare and safety through structural strength, stability, lighting and ventilation, and the conservation of energy, as well as protecting occupants from risk of fire.

Building codes are designed to govern all types of construction of public, commercial, retail and residential buildings. Building regulations are divided into several branches covered by a set of documents, the main areas being the building code, mechanical code, electrical code, and plumbing code. There are two objectives behind a building code: the first is to save lives, protect public health, safety, and general welfare, as these relate to the construction and occupancy of buildings; and the second is to protect the shape and form of properties. To achieve these objectives, building regulations generally specify minimum standards for comfort and safety that must be met in new construction and major renovation [54].

According to building standards in the USA, there are requirements and specifications for thermal conductivity that are limited, and any building should stay within that limit regardless of the construction. To achieve the requirement of the U-values, several methods of wall design could be followed by using different types of insulation, air gaps, and methods of assembly between the wall parts. The foundation and flooring of a typical house in a hot/dry zone, such as Arizona, consist of a monolithic slab beam assembly, with the slabs thermally isolated from the ground. Walls are wooden frames covered on the inside with gypsum plasterboard, then thick cavity insulation, then oriented strand board (OSB) or plywood, building paper to work as a bond, metal lath, then a traditional cement stucco or polymer-modified (PM) on the outside. The flooring consists of a wood frame covered by OSB or plywood. The roof structure, starting from the inside, normally gypsum boards, plywood, insulation, plywood and, in the end, covered by rubber roofing. The roofs are not generally flat and are covered by shingles sitting on sheathing, then cavity clearance under the sheathing, then cavity insulation [55].

The International Energy Conservation Code (IECC) has a list of U-values (thermal conductivity) for each type of building zone [53], which sets the material and material resistivity for that particular part of the building. It should be noted that this is always pushing towards a greater resistivity in buildings. In the USA, a thermal conductivity (U-value) code is specified for each zone. For areas with a hot and dry climate, the thermal resistivity requirement is as follows: walls and floor R-13 (U=0.438 W/m^2.K), ceiling R-30 (U=0.189 W/m^2.K) and the thermal conductivity of the windows should be U=0.65 W/m^2.K [56]. According to the ASHRAE 2009 Fundamentals, roofing is very different in terms of the design and the materials used, but roofs should all share a point by having considerable good-quality insulation, as the thermal conductivity U-factor for any design ranges from 0.227 to 0.452 $W/m^2.K$ [45]. The updated Saudi code [57] has a list of required construction and U-values as part of the total building code.

In summary, most of the countries have their own construction code under a different name. The criteria, priorities, and focuses are different from one country to another. Climate and tradition have a very important part to play in the design of building codes. Some countries do not have their own codes, or these might be very old, so they adopted those codes by giving very careful consideration to the climate, local materials, and building traditions, as these might not suit every location and priorities are different from one country to another.

2.5 Internal and Activity-Related Parameters

The main purpose of air conditioning in buildings is to provide comfortable, reasonable and acceptable indoor conditions for the occupants. Inadequate air in a building will affect the comfort and health of the residents and even the productivity of the people living in the building. In general, occupants are affected by indoor conditions. Internal thermal comfort can be improved by making sufficient changes to the indoor air conditions and maintaining a satisfactory environment with better air quality and air temperature in the building, as bad air quality and inadequate air temperature can cause sick building syndrome symptoms and reduce the productivity of the occupants. For the aforementioned reasons, the minimum values of a building's thermal comfort and internal air quality are described and defined by many researchers for different national and international standards.

The internal heat gains produced by the residents' activities and the equipment in the building are a very important parameter that has a direct impact on energy usage for air conditioning in the building, consequently increasing the cooling load and energy usage. The most obvious internal parameters are occupants and occupancy, equipment and lighting. The heat gain from these three parameters is based on data obtained and collected through surveys for different building types and human activities in cases in which measured data do not exist. The empirical approach is the most applicable way to calculate internal heat gains [58]. ASHRAE [45] has set values regarding occupants' heat gain, and the Chartered Institution of Building Services Engineers (CIBSE) in England [58] has the same rates for the human heat energy that is added to the building while it is occupied. The values change according to whether the occupant is male or female, an adult or a child. The gain rate also depends on the occupant's activity, such as sitting, reclining or walking.

Lighting in the building has an obvious impact on the heat gain and thus the energy consumption for air conditioning. The heat gain from lighting comes from lighting emitting elements. The heat gain from lighting is convective and radiative: the heat from light directly to the air is called convective heat gain, and the heat produced by the fittings is radiant heat gain [45]. ASHRAE (Chapter 30) [59] includes all lighting energy consumption and the method for releasing heat. Finally, electric equipment or appliances also influence internal heat gain, especially if the zone has more than one item of equipment. Another method of lighting power density (LPD) could be used to estimate lighting heat gain/m^2 in a zone (Chapter 18)[45].

Ahmed et al. [60] investigated occupants' schedules in energy simulations. The heat losses from an occupant's body through convection and radiation are important data to assess the energy consumption of internal environments and usage. They reported that the heat loss from a body mainly depends on the type of activity. Internal air temperature, relative humidity (RH) percentage level, air velocity, as well as clothing have a significant influence on total heat losses from the occupant, leading to typical values for summer and winter. When Mustvilas et al. [61] investigated the energy consumption in buildings, they inserted energy consumption into an equation based on hourly daily heat gains. They found that the calculation of annual energy consumption could not be performed based on annual parameters.

Coskun et al. [62] researched the importance of internal gains for building's cooling design in Izmir in Turkey. A third-floor apartment occupied by three adults was chosen for the study. The building was uninsulated from the outside and the heat that dissipated from all internal parameters, such as lighting, equipment, and occupancy was calculated using DesignBuilder software. The internal temperature was observed during the three weeks of the test and a dynamic simulation program was used to determine the annual cooling energy consumption using live data taken directly from outside conditions via a data logger. The study showed that the largest part of the cooling load in the apartment was due to the equipment and other systems that generate heat, although the amounts were found to be small: 0.36% for lighting, equipment was 0.63%, and occupancy 0.81% of the total cooling load.

In summary, the heat that the body of an occupant generates depends on the activity in the building, air movement, and humidity. The equipment in the building has a large impact on energy and cooling load; lighting has an impact on cooling load and energy consumed, as it adds convective and radiative heat to the building and using energy saver equipment and light-emitting diode (LED) lights would lead to a decrease in the load inside a building. Although an occupant’s activity cannot be changed, increasing air movement would improve the amount of heat a body generates.

2.6 Indoor Thermal Conditions and Air Quality

Indoor air quality: Keeping comfortable indoor conditions by achieving good air quality is a vital issue because people spend 90% of their lives either indoors or inside a building, and approximately 60% of this time is spent at home. Ventilation is a necessary part of providing good internal air quality (IAQ). The purpose behind ventilation is to provide occupants with fresh or outdoor air for comfort and ensure healthy conditions. Infiltration sometimes provides an adequate rate of outdoor air into the building because overventilation will cause heat gain/loss, which directly raises or lowers the internal temperature, leading to a rise in energy consumption in cooling/heating to keep the internal temperature at the desired level.

ASHRAE’s Ventilation Standards 2007 [63] set a minimum ventilation rate in residential building zones and defines air quality as a rate showing 2.5 L/s per person or 5 cfm/person, which is equivalent to 0.3 L/s/m^2. This rate is much higher in health care or office buildings, which require 8.5 L/s. The scope of this standard applies to all spaces intended for human occupancy with an adequate requirement of clean air; this rate is not adequate for a smoking environment. The CIBSE [64] advice on air quality sets a minimum for fresh air at 0.3 L/s floor area, which is the same as the ASHRAE 2007 [63] rate. However, the CIBSE recommends an optimal ventilation rate of 10 L/s per person with humidity between 40-70% and 24 °C as an internal temperature that achieves a comfortable air quality.

Indoor thermal conditions: According to ASHRAE, thermal comfort is the state of mind to be able to express satisfaction of a particular environment and conditions [45] and to be comfortable thermally means that the individual is normally clothed and feels neither warm, hot nor cold in that location. If an individual's body is losing heat, it means that the person is cold or, if the body is receiving heat, it means the person is warm or hot, depending on the rate of heat loss or gain [65]. Internal conditions should be taken into consideration when designing the air conditioning for a building to maintain the comfort level for occupants. Six parameters affect indoor comfort and have a direct impact on the occupants: metabolic rate, clothing, air dry-bulb temperature (DBT), mean radiant temperature, air humidity and air velocity. The first two parameters are individual and personal factors, while the last four are physical parameters. The six parameters are outlined in more detail below.

Metabolic rate: This is the amount of heat generated by a person over a certain period or the rate of work done during routine physical activity. It can be measured in different units and varies depending on the individual, the activity and the conditions. For an ordinary person with 1.8 m^2 of surface area and an activity performed continuously, the unit to express the metabolic rate per unit DuBois is the Met, which is the rate of a sedentary person (quietly seated): 1 Met = 58.1 W/m^2 = 50 $kcal/h/m^2$. Table 2-6 shows the heat generated for different activities.

Table 2-6: ASHRAE metabolic rates [59]

Activity	Sleeping	Reclining	Seated, quiet	Standing, relaxed	Walking 0.9 m/s	Walking 1.2 m/s	Walking 1.8 m/s
Met	0.7	0.8	1	1.2	2	2.6	3.8
W/m²	40	45	60	70	115	150	220

ASHRAE [59] has a long list of metabolic and heat rates for each activity. This rate is important for modelling energy and sizing heating/cooling equipment. It is different for adults and children and for elderly people [66].

Clothing: One of the factors that affect comfort is clothing. Clothes counted as an insulator, separating the human body from the surrounding environment. The amount of clothing a person wears can be calculated using clothing insulation (Clo): 1 Clo = 0.155 m^2.K/W. In summer, when someone is wearing short-sleeved or thin clothing, a Clo is 0.5; in winter, when extra clothing wore, Clo is 0.9 to 1, as shown in Figure 2-3. The ASHRAE Fundamentals have more details of this term in ISO 7730 [67], and ASHRAE 2009 [45] has a list of clothing values to use in energy modelling, especially for thermal comfort. ISO 7730 gives a list of the relationships between activity level (metabolic rate), an occupant's clothing, temperature and air velocity [65].

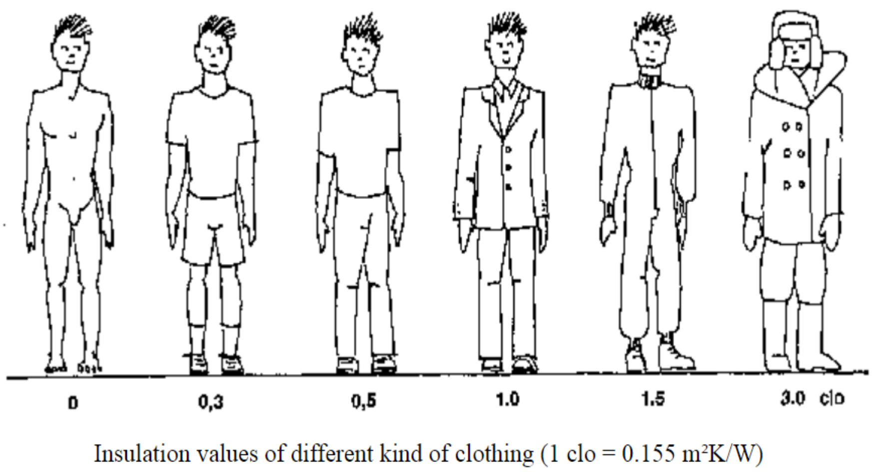


Figure 2-3: Occupant's clothing, where 1 Clo = 0.155 m^2.K/W [68]

Havenith et al. [69] studied a database of static clothing thermal insulation and vapour permeability values of non-Western ensembles for use in ASHRAE and ISO 7730 and ISO 9920. They used experiments to investigate 52 non-Western clothing ensembles for indoor use ranged from 0.2-1.7 Clo. Four different manikins were tested with full clothing. Substantial differences in insulation were noticed for the different manikin shapes and sizes.

Air dry-bulb temperature: This can be defined as the temperature of the air surrounding the human body, which governs the heat flow between the body and the air. Normally, the temperature of the air fluctuates, so heat exchange among human bodies is a continuous process. Neither far distance from the human body that determines the heat flow, nor the very close Air temperature is representative, as it is going to be influenced by the very close boundary. Air temperature is a very important factor in thermal comfort. Radiant temperature and room air temperature can be combined to form operative temperature, as in the following equation:

$$To = \frac{T_{rad} + T_{air}}{2} \tag{2-1}$$

Where,

To is the operative temperature in °C

T_{rad} is the mean radiant temperature in °C

T_{rad} is the surrounding air temperature in °C

Mean radiant temperature: Mean radiant temperature is a very complex variable among the heat-balancing temperatures. This temperature is a significant variable for human body thermal calculations and describes the thermal radiation of an individual from all directions. It is defined as "*the temperature of a uniform enclosure with which a small black sphere at the test point would have the same radiation exchange as it does with the real environment*" [70]. As heat is exchanged, to calculate radiant temperature, there is a set of equations with upper and lower limits. The value of the radiant temperature depends on the direction, such as floor to ceiling; if the direction is not specified, the maximum temperature should be taken [45].

Walikewitz et al. [71] investigated a method to simplify the past studies of radiant temperature (T_{rad}). According to the researchers, T_{air} is equal to T_{rad} under indoor conditions, and they examined the deviation between the two parameters (T_{air} and T_{mean_rad}) when integrated into an indoor climate context. Four rooms in Berlin were taken as part of the study from 16/08 to 02/09 in 2013. The study showed that deviations between the different methods of obtaining T_{mean_rad} were negligible for indoor environments and, in most cases, the difference between T_{air} and T_{rad} was so small as to be negligible.

European Union's (EU) advice is to use the operative temperature in designing building air conduit systems [72]. The EU standard sets the operative temperature in the cooling season as 24-26 °C and for the heating season between 20-24 °C. The limits for the comfortable temperatures are shown in Figure 2-4.

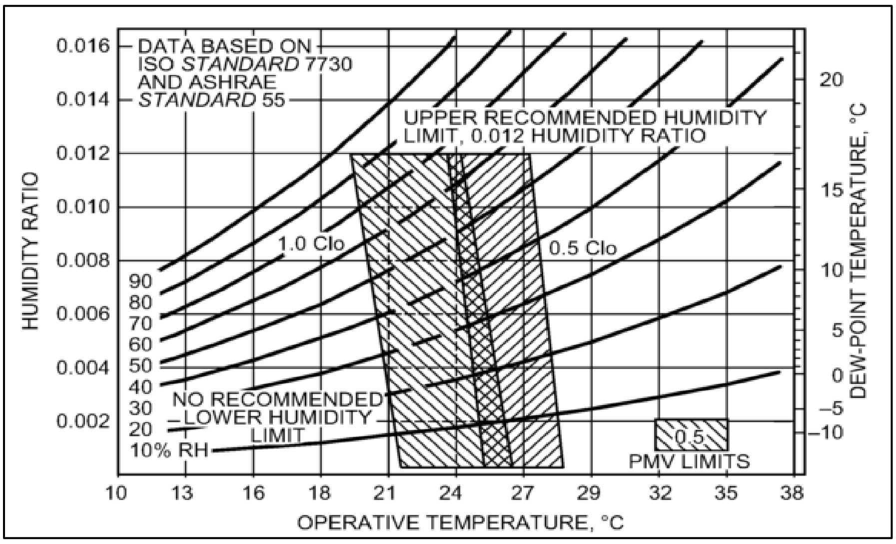


Figure 2-4: Operative temperature range [24]

The Iraqi Registration of Air Conditioning has set the table of internal temperatures in different zones in a home [73], such as 26 °C for a kitchen. Roshan et al. [74] investigated the thermal comfort boundaries, temperature and relative humidity of 148 weather stations in Iran for more than a 20-year period. A Giovanni chart was used and showed that only 18% of the 148 stations fell under thermal comfort bioclimatic conditions. It was found that the upper threshold component varied from 22.6-25.94 °C. The findings present updated thermal comfort boundaries that can be used by architects, engineers and policymakers in their efforts towards more energy-efficient homes and high- quality indoor and outdoor living environments.

Air humidity (RH%): Humidity is as significant a parameter as temperature for air conditioning investigations and has a major impact on human comfort at high temperatures when it slows or impedes the evaporation rate through sweating. According to the CIBSE Guide A 2006 [75], acceptable humidity is in the range of 40-70%, with an optimum value of 65% for comfortable air temperature. The feeling of humidity has a wide range of expressions and differs from one individual to another. For example, suddenly entering a high humidity zone can provide transient warmth from the absorption of moisture into the clothing, but entering a dry zone from a humid one provides a chilling effect. Harimi et al. [76] identified a new relationship for optimum internal relative humidity based on the air temperature in hot and humid areas. The investigation found that the people involved in the study were thermally comfortable at a relatively wide humidity range. The mean relative humidity corresponding to the optimum comfort temperature was close to 73% RH. Anton et al. [77] who are ASHRAE members investigated the internal humidity design and control. Part of their research conclusion was that the humidity in residential buildings is a personal choice and that should not be left for the designer or the modeller, and the design of the humidity should be left for the occupier the and personal judgement rather than adequate information.

Air velocity: This plays a large role and has an impact on thermal comfort. For example, when it is hot, the body tries to cool itself down, produces sweat, which then evaporates into the surroundings, and the close air becomes saturated with moisture. Moving the air at speed and bringing fresh air lowers the humidity around the body, and the process of evaporation from the body by sweating can continue. This mechanism of convection (heat transfer) moves the generated heat by metabolic processes from human skin and into the surrounding air, leading to continuous cooling; the higher the velocity of the air, the more effective the process. The air velocity in buildings has a limit for providing comfort and, if the velocity crosses that limit, it becomes unpleasant or can cause constant awareness of air movement or sometimes a sensation of draught.

Boduch et al. [78] studied comfort and concluded that any air velocity up to 0.25 m/s is unnoticeable, 0.25-0.5 m/s is pleasant, 0.51-1.016 m/s would be pleasant and the occupant would notice air moving around him/her, 1.01-1.52 m/s is annoyingly draughty, and air moving at more than 1.52 m/s is annoying and requires attention and correction. The ASHRAE Fundamentals 2009 [45] provides a list of velocity ranges for each metabolic condition to be used in finding convective heat transfer coefficients. Neutral velocity is 0.25 m/s or less, noticed with dissatisfaction by 15% of the population, but the dissatisfaction of the mean air velocity decreases with an increase in the operative temperature. According to EU standards [79], the recommendation is to consider and use the operative temperature when designing HVACs in buildings. The standard classifies buildings into four types of thermal comfort according to the level of expectancy, as shown in Table 2-7. The classification is based on the Predicted Percentage of Dissatisfied Index and the Predicted Mean Vote (PPD-PMV), which analyses the votes of a large group of people based on heat balance and is part of the Indices of Feeling. The PPD and PMV ranges are shown in the table below.

Table 2-7 Thermal comfort levels and expectations

Level or category	Predicted percentage of dissatisfaction %	Predicted mean vote
1	Less than 6	-0.2<PMV< 0.2
2	Less than 10	-0.5<PMV< 0.5
3	Less than 15	-0.7<PMV< 0.7
4	Bigger than 15	Either PMV< -0.7 or PMV>0.7

In summary, maintaining indoor air condition and quality is extremely important, as people spend around 90% of their lives inside buildings. It has been calculated that 2.5 L/s/person is an adequate rate of fresh air with a relative humidity of 40-70%. The amount of clothing a person wears in summer is around 0.5 Clo, although this depends on the individual. The T_{air} could be used as the operative temperature when the difference with $T_{radiant}$ is small. In residential buildings, the ideal metabolic rate is Met 0.7-2 (40-115) W/m^2. Comfort is highly complex because it differs from one person to another at the same time and environment. In summer, 24-26 °C is the temperature set for comfort; the comfort level limit could be higher by increasing air velocity and relative humidity. One parameter alone cannot decide the comfort level.

2.7 Cooling Systems in Residential Buildings

2.7.1 Direct Expansion (DX) Systems

The use of direct expansion systems is growing rapidly because of their ability to eliminate the need for ductwork and piping. The easy installation of DX systems and the reduction in the overall cost of the system is one of the key reasons behind their popularity. Other advantages are: i) it is easy to test, adjust and balance the system; ii) individual sections can be operated without running the entire system in the building; iii) it offers comfort under varying load conditions; iv) a low noise level; v) minimal ceiling or wall space needed; and vi) good relative humidity control. Window air conditioners, mini-split, and packaged units are the main types of DX system [80].

The split type is very efficient compared with other air conditioning systems. It consists of two main units: a condensing unit located outdoors, and an internal unit comprising a fan and a coil for supplying cool air. These two (internal and external) units are connected by a liquid and suction line to supply cooled air. The system is very efficient and has more advantages than the window type. It does not make a noise during its operation, which is the case with the window air conditioner unit, because the indoor part employs a quiet fan. The split system also exhausts the heat away from the room, as the condensing unit is in the outdoor part. Consequently, the split cooling system has more cooling efficiency and less energy consumption than the window type of cooling system [81].

Packaged air conditioners are used for cooling larger spaces or more than two rooms. There are two types of arrangements with the package unit. In the first type, all the components (compressor, condenser, expansion valve and evaporator) are housed in one box. The cooled air is thrown by a large blower and flows through the ducts and is distributed to many rooms. In the second arrangement, the compressor and condenser are kept in one casing. Packaged units are more expensive than window units. The average life cycle of a packaged air conditioning system is as short as 10 years, and they consume a higher rate of electricity than window air conditioning units[82]. The operating principle of the multi-split air conditioning system is similar to that of single-split air conditioning; the single difference is that the outdoor unit could be utilized by four indoor units [11].

2.7.1.1 Split Air Conditioners and Working Principles

A split air conditioner unit is separated into two different components: one outdoors and the other indoors. The outdoor section is a compressor that initiates the cooling process, while the indoor component consists of an evaporator and a fan. The two pieces are connected by a set of tubing, and electrical wires also called lines, and are used to transport air between the two pieces, the components are shown in Figure 2-5. A split air conditioner is considered ductless due to the aforementioned lines. The wires and tubing are very small in comparison with the large ducts in central air conditioning systems, which is why this is called a mini-split air conditioner system.

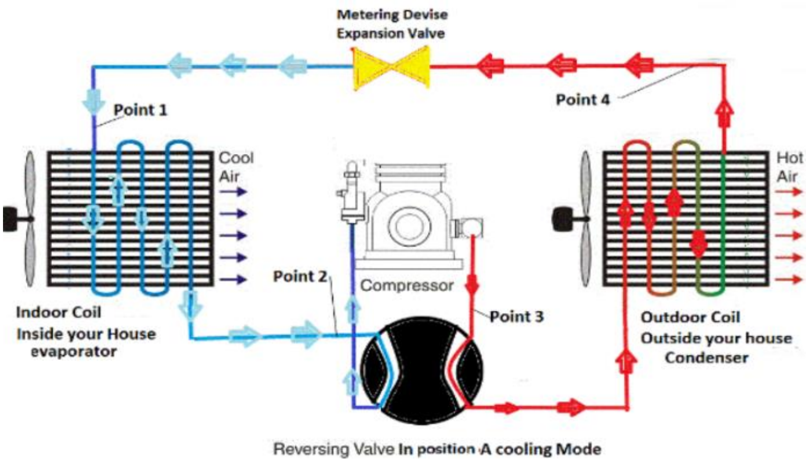


Figure 2-5: Mini-split air conditioner components [83]

The compressor in the unit is controlled by an internal thermostat that detects the indoor temperature. As soon as the thermostat senses warm indoor air, it activates the compressor. The compressor then increases the pressure and temperature of the refrigerant gas to circulate it through a pipe. The high-pressure and high-temperature gas reaches the condenser, cools and changes from a gas to a liquid phase, then the chilled liquid flows through the indoor tubes before reaching the evaporator of the split system. Inside the cooled space, the evaporator fan sucks the warm air from the room. The warm air flows over a chamber containing cold liquid refrigerant, the air cools and is circulated back into the room by the fan. The same process is repeated until the thermostat detects the desired indoor temperature. The working principle and position of the system shown in Figure 2-6.

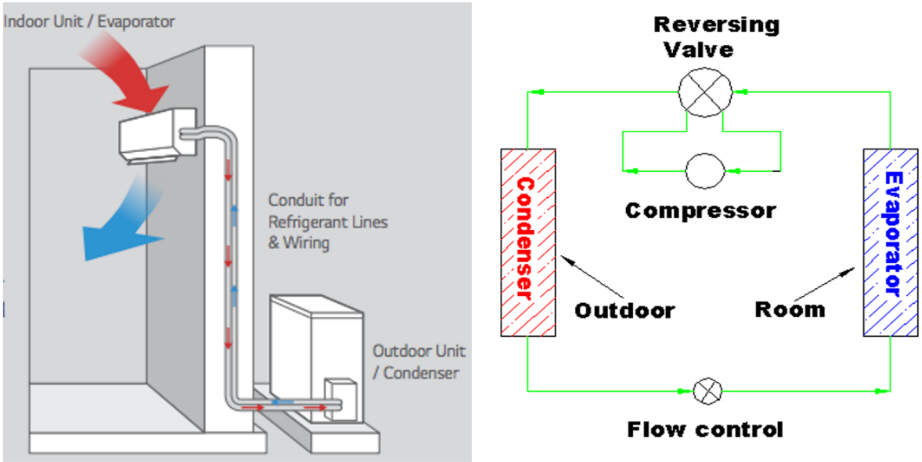


Figure 2-6: Position and working principle of split air conditioner [84]

The performance of the split type of air conditioner system depends on the surrounding temperature of the outdoor unit, and the coefficient of the performance of the system declines by around 3.0% when the surrounding temperature of the outdoor unit rises by 1 °C. Architects are restricted from installing the outdoor unit in the building shafts (light wells) in order to hide it and maintain the appearance of the building. This dramatically reduces the unit's performance and causes problems with the air conditioning system due to the blockage of the heat rejected by the condensing units, which increases the surrounding temperature of the outdoor part. This rise in surrounding temperature leads to significant degradation of system performance, particularly for the systems on the upper floors [85]. The performance of a split unit also depends on its coefficient of performance (COP). The COP varies with the working conditions, such as the air in the room and the condenser cooling condition. Cooling system performance is enhanced with higher room temperatures and lower condenser temperatures [86].

2.7.1.2 Overview of the Related Research and Development (R&D) Work

Sutherland et al. [87] evaluated a ductless mini-split system in a hot and humid climate, monitoring 53 homes for over three years. The performance of a mini- and a multi-split system were compared with the standard conventional ducted system in the same hot-humid climate. Both the mini- and multi-split systems presented significant cooling energy savings, as the mini-split system could save 33% (6.7 kWh/day) for space cooling. However, the multi-split system exhibited problems with controlling indoor humidity and space temperatures. Joudi et al. [88] studied the steady-state performance of residential air conditioning systems experimentally, using R22 refrigerant is a type of (Chlorofluorocarbon) and other possible refrigerants of R290, R407C, and R410A at high ambient temperatures. They determined the air conditioning system parameters, such as the optimum refrigerant charge, cooling capacity, COP, pressure ratio, power consumption, and power per ton of refrigerant (1 ton=3.516 kW, it is the cooling capacity of an air conditioning system). The tests were run under high ambient temperatures of up to 50 °C for all refrigerants. Two split-type air conditioners of 1 and 2 ton refrigerant capacity were used. The air-conditioned space temperature was set to 25 °C. The study concluded that R290 had the highest COP among the refrigerants, and COP decreased with an increase in the ambient temperature for all refrigerants. The 1 and 2 ton refrigerant split air conditioners had the lowest COP when R410A was used. Thus, although R410A is not the ideal choice for an air conditioner in hot climates, it would be useful for heat pump applications at low ambient temperatures because the heat rejection of the condenser is the highest with R410A. With regard to the environmental impact, the air conditioner with R290 required less charging and it is a good alternative to R22 for high ambient temperatures.

Nethaji et al. [89] conducted experiments to study the energy conservation of a split air conditioner using loop heat pipes. They fabricated three loop heat pipes and filled them with ethanol as a working fluid, then combined them with the cooling coil of the split type air conditioner. Under experimental conditions of 22-25 °C indoor temperature, 50% RH and a constant air flow rate, they determined that COP could be improved by 18-20%, the apparatus dew point (ADP) declined from 11.8 °C to 8.9°C, the DBT of the air supply increased from 11.8 °C to 16.3 °C and the dehumidification ability of the air conditioning system improved by 30%. When all three loop heat pipes were employed, the latent heat recovery was found to be 482 W. Generally, the study concluded that the employment of loop heat pipes in a split air conditioner was not just to reduce energy consumption, but could also enhance the moisture removal ability of the system. Yau et al. [90] studied the effect of weather variation on split air conditioners in the tropics, Malaysia in particular, by investigating the air-ducted blower of the systems on cooling capacity and sensible heat factor. The researchers determined that an increment of 1 °C of the surrounding temperature led to a reduction of 2% in the system's COP and the total cooling capacity of the air-ducted blower of the system, the sensible heat factor reduced by 2% as and the cooling capacity will be reduced by 5.5% as predicted for the years 2020 to 2080.

2.8 Evaporative Cooling Systems and their Working Principles

2.8.1 Direct Evaporative Cooling (DEC) Systems

DEC systems are one of the oldest cooling systems used to produce indoor comfort for conditioned spaces. The cooling procedure starts by passing dry air directly through a wet pad or surface, as shown in Figure 2-7. Cooling pads play the main role in the energy performance and cooling efficiency of evaporative air coolers.

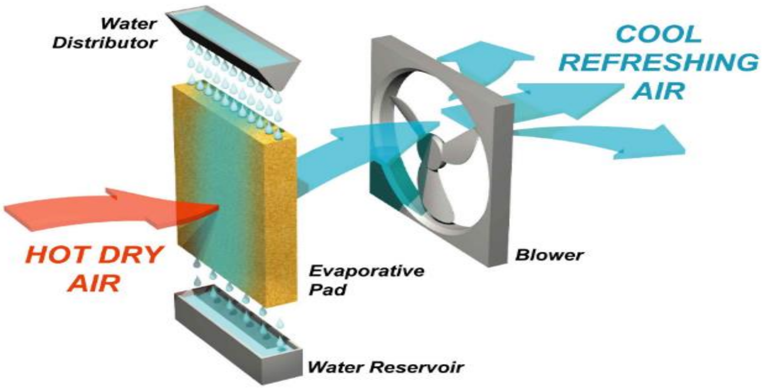


Figure 2-7: Cooling procedure of a direct evaporative cooling system [71]

Heat exchange between the inlet air and the wet surface occurs, and the sensible heat of the inlet air evaporates water from the contacted surface, consequently lowering the DBT while increasing the humidity of the air at a constant wet-bulb temperature of the same inlet air.

Heat exchange is a constant enthalpy process or an adiabatic process, as shown in Figure 2-8, which means the sensible heat absorbed from the DBT of the inlet hot air has the same inlet wet-bulb temperature (no sensible cooling occurs) [91].

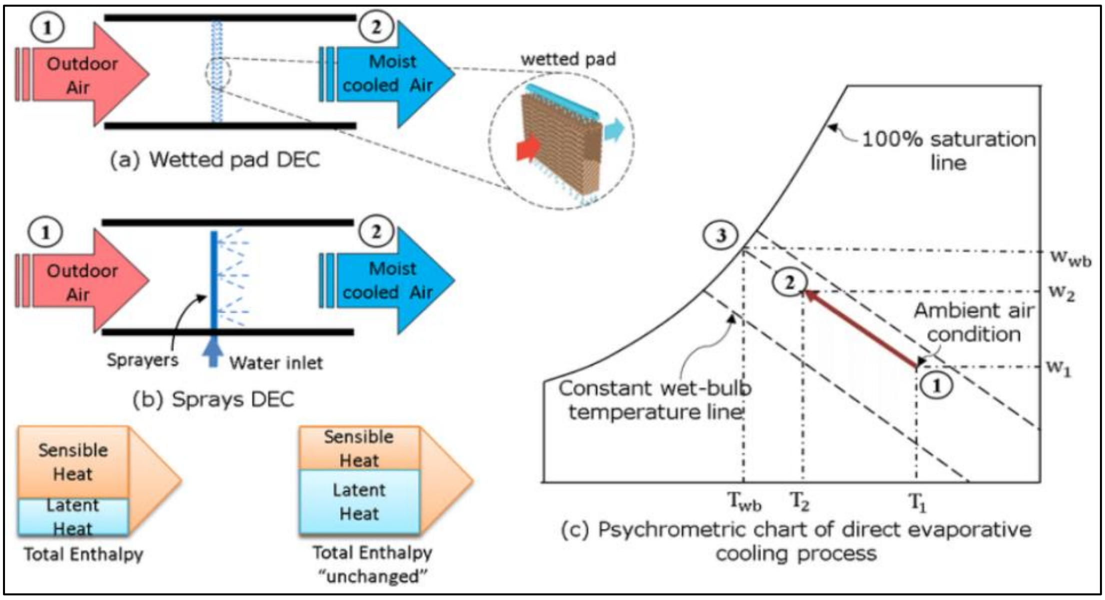


Figure 2-8: Heat exchange process of direct evaporative cooling [73]

Although this type of cooling system is cheap, easy to install and simple to use, as shown in Figure 2-9, its application is limited by the wet-bulb temperature of the air, as it is not recommended for air with a wet-bulb temperature over 21 °C [92]. In this cooling process, wet-bulb effectiveness could reach 70-80% due to the short contact time between the air and the wet surface and the possibility of the inadequate water content of the pads. Another limitation is that water and air will reach an equilibrium point of the same wet-bulb temperature. Consequently, the system will not be able to cool the air to a lower temperature than its wet-bulb temperature [93]. Therefore, it is more feasible for dry and mild climates than humid climates.

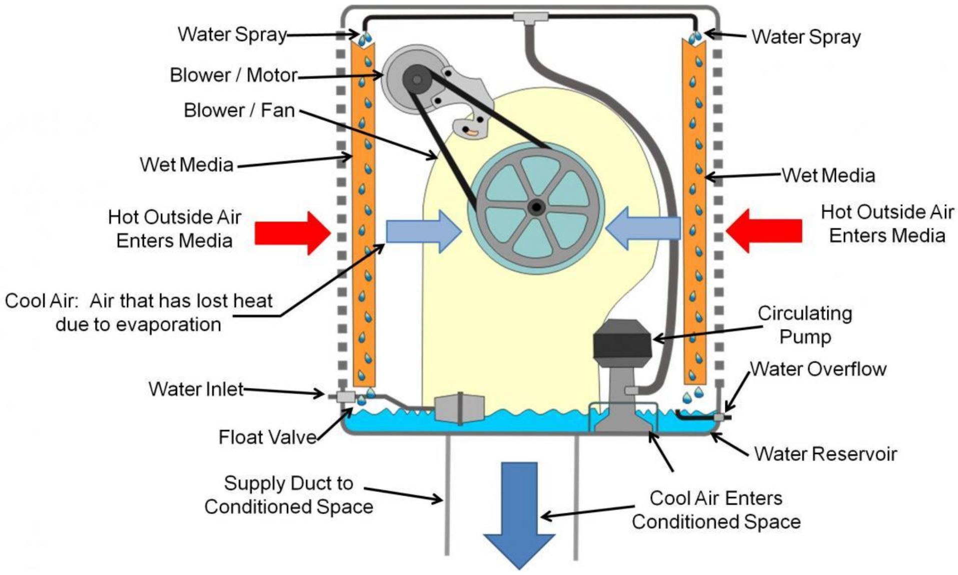


Figure 2-9: Direct evaporative cooler, swamp cooler [76]

2.8.2 Indirect Evaporative Cooling (IEC) Systems

The primary air in a direct evaporative system includes a high amount of water due to the direct contact with water, resulting in air conditioning with high humidity, which causes discomfort for the occupants. To overcome this disadvantage of direct evaporative coolers, indirect evaporative cooling systems were developed. In an IEC system, a heat exchanger is used to separate water from the air. The evaporation of water occurs on one side of the heat exchanger, along which the secondary air transfers, and, at the same time, the primary air moves across the other side. The plate cools by evaporation of the water, producing heat transfer between the plate and the primary air, as shown in Figure 2-10. In the meantime, the secondary air removes the vaporized water from the wet side of the plate (channel). Therefore, cooling the primary air occurs without adding moisture. This advantage of IECs enables them to be used as an alternative to a mechanical vapour compression system [94].

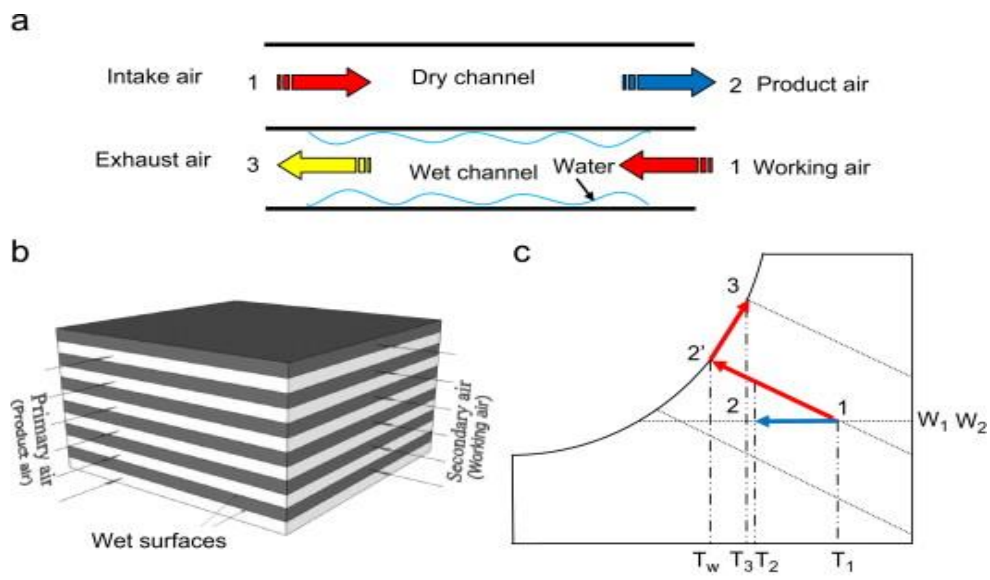


Figure 2-10: Conventional IEC heat and mass exchanger. (a) Working principle of indirect evaporative cooling, (b) Configuration of the type IEC heat and mass exchanger, and (c) Psychometric illustration of the air treatment process in the IEC heat and mass exchanger [94]

2.8.3 Combination Systems

Indirect cooling is often combined with a second direct evaporative cooling, as shown in Figure 2-11, to raise the efficiency of the overall system. The first indirect cooling drops the dry-bulb and wet-bulb temperatures of the inlet air. Then the outlet air from the first (indirect) cooler enters the direct evaporative cooler for further cooling with added moisture. The secondary air in indirect cooling could be fresh outdoor air or the exhaust air from a conditioned room, as shown in Figure 2-11. This combined system is considered more economical due to the significantly low electricity consumption in comparison with air conditioning systems, but the water consumption should be taken into consideration as well [95].

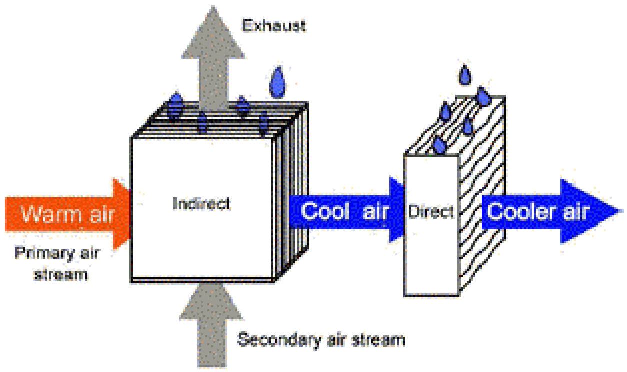


Figure 2-11: Indirect/direct evaporative cooling system [79]

Researchers are now focusing on new approaches to improving the efficiency of IEC systems. The combination of IEC and DEC and the multi-stage combination of IEC are examples of possible methods and the effectiveness of the IEC/DEC differs over a range of 90-120% [96]. The combination of IEC and DEC could improve the COP by 20% in comparison with separate IEC and DEC systems [97]. The combination of a dew point evaporative cooler and a conventional vapour compression air conditioner works efficiently in hot and dry and hot and moderate-humidity climates but is not suitable for high-humidity climates [98].

2.9 Dew Point Evaporative Cooling Based on the Maisotsenko Cycle (M-Cycle)

This method of adiabatic cooling was patented in 1987 by Valery S. Maisotsenko and Alexander N. Gershuni in the former Soviet Union. It was patented as a "Method for indirect-evaporative air cooling" in the USA in 1990 [99]. The Maisotsenko cycle (M-cycle) is considered an improved design of indirect evaporative cooling, as it can successfully keep the air temperature below the wet-bulb temperature and near the dew point temperature, as well as retaining the humidity ratio of the air produced. Low energy demand is a significant advantage of this technology over other indirect evaporative coolers. The heat exchanger comprises dry and wet channels, divided by an impenetrable thin film partition that prevents moisture penetration between the channels' absorbent material to distribute water evenly with a thin layer of waterproof coating [100].

2.9.1 Dew Point Indirect Evaporative Cooling Working Principles

The system is based on a heat exchanger consisting of multiple layers of sheets all stacked together as one bulk. The sheets are placed in a particular order, whereby one side of the sheets are covered with a fabric or wetting material, glued or heat pressed onto thin metal or plastic, giving the sheet the strength and ability to stop water from penetrating. Two similar materials are each placed opposite another sheet of the same material, separated by the channel gap. Together they form the wet channel of the heat exchanger. The other gap, which is between two metal or two plastic sides, forms the dry channel of the heat exchanger.

The intake air (ambient air) taken into the dry channels from the lower part of the heat exchanger bulk on the left-hand side of the stack. The principle behind the dew point cooling system heat exchanger operation is as follows. Air flows through the dry channels upwards along the length of the channels and is divided into two parts at the end of the channel: one part of the air stream keeps flowing in the same inlet direction and is finally sent into the space where cooling is needed as conditioned air (product air); the other portion of the air stream is directed into the adjacent wet channel through the many holes or perforations on the sheets, where the surfaces are soaked and wetted by the sprayed water.

When a portion of the air is directed into the wet channel, the wet channel allows heat to be absorbed through the channel walls by vaporizing the water on the wet and soaked surfaces. The air in the wet channels flows in the opposite direction and finally exits to the atmosphere from the bottom of the heat exchanger (on the right-hand side of the stack). At the beginning of the process, the dry channels contain both working air and product air, while the wet channels take only working air, a portion of the intake air. The remaining intake air flows out as supply or product air (conditioned air to be supplied to space), which was cooled near the dew point temperature of the entering air because of the total heat transfer (i.e., sensible and latent heat) with the working air in the adjacent wet channels. Latent heat and sensible heat are exchanged through vaporizing the water on the wet surface into working air and absorbing the heat through the channel walls from an adjacent dry channel to the wet channel. The working air in the wet channels is humidified (vaporization of water) and eventually heated (absorbing heat from adjacent channels). Figure 2-12 shows the principle of the dew point heat exchanger model and the dry and wet channels.

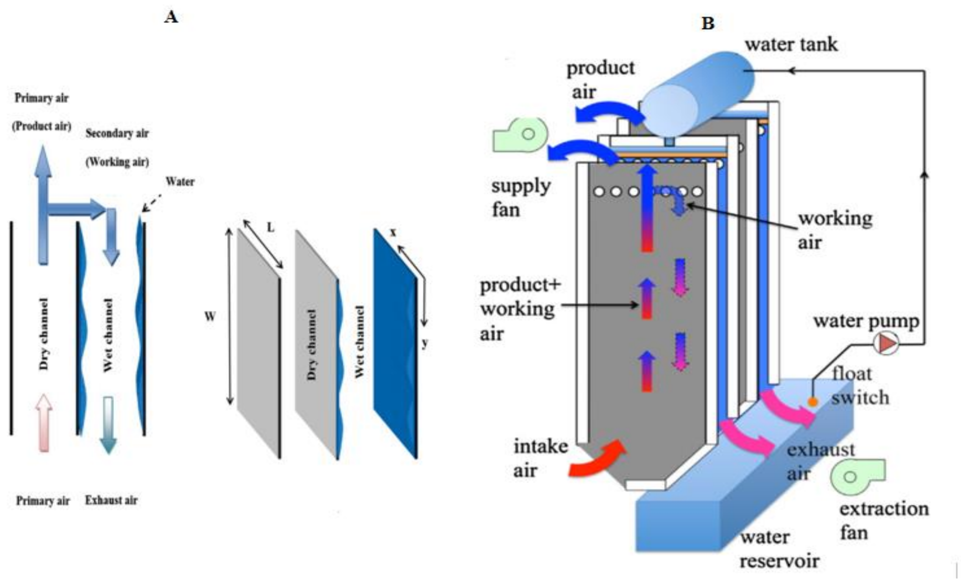


Figure 2-12: Working principle of an indirect evaporative dew point cooling system [19]

The air treatment process that occurs in the heat and mass exchanger (HMX) is illustrated in Figure 2-13 a-b, showing the psychometric chart of the treated air in the heat exchanger. The intake air in the dry channel faces a constant moisture cooling process Figure 2-13 (state 1-2) until reaching almost the dew point temperature of the intake air because of the improved heat and mass transfer between the product and the working air. The maximum heat exchange occurs while the inlet temperature of the working air (part of the intake air) is fully pre-cooled near the dew point of the intake air.

Meanwhile, in the wet channel, when the water evaporates, the working air faces a constant enthalpy cooling process, until it reaches a saturated state (process 2 to 3'). Flowing without interruption in the opposite direction, the saturated working air exchanges heat with the air in the dry channel sensibly and latently until exiting the heat exchanger (from state 3' to 3). The sensible and latent heat transfer occurs concurrently along the way.

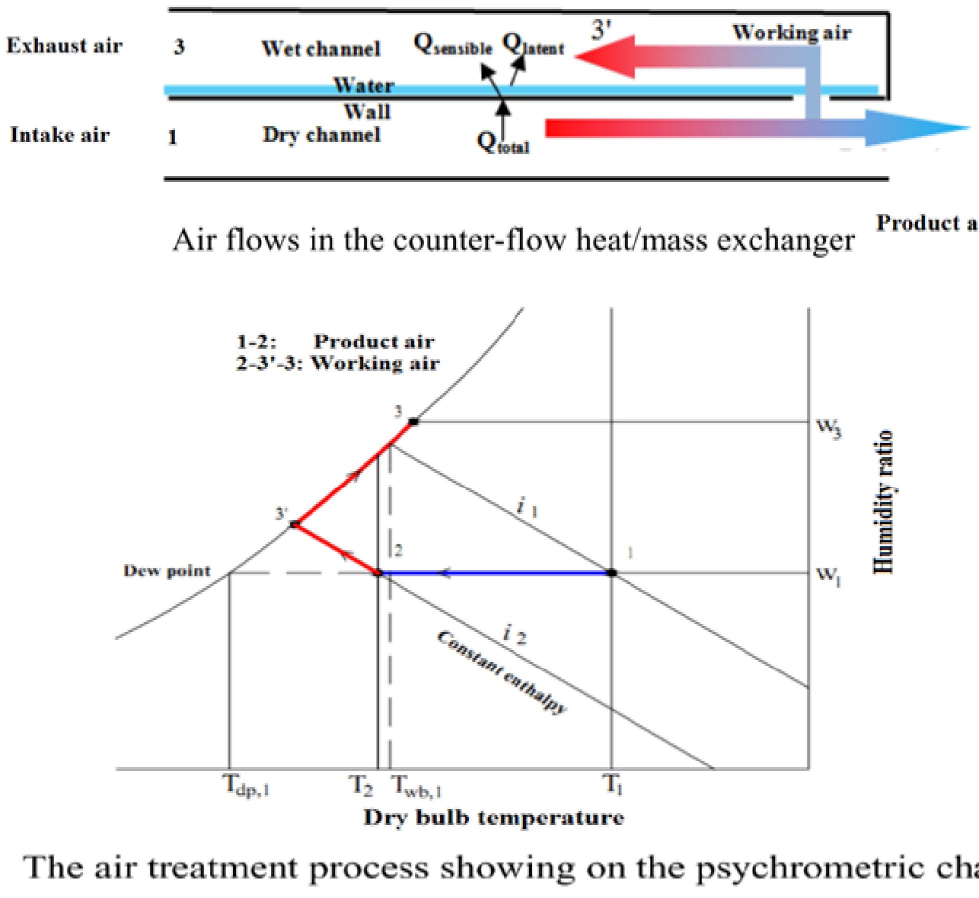


Figure 2-13:Counter-flow dew point indirect evaporative cooler's air treatment process [101].

2.9.2 Performance Evaluation Criteria for IEC Systems

The parameters for evaluating indirect evaporative coolers are: supply air flow rate and temperature, secondary/primary air ratio, wet-bulb effectiveness, cooling capacity, energy efficiency, and water and power consumption. The most vital and effective parameters are defined below.

2.9.2.1 Secondary/Primary air ratio

In an IEC system, the secondary air flows in the direct section, whereas the primary air flows in the indirect section. The secondary/primary air ratio influences the performance of the cooler. In the case of a constant air flow rate, the effectiveness of the cooler improves when the secondary/primary air ratio increases, because the high percentage of secondary air flowing in the direct section absorbs sensible and latent heat from the primary air, although the supply air flow rate of the cooler decreases. For some IEC systems, the secondary air is the fraction of the intake air entering the indirect section. The secondary/primary air ratio can be replaced by a similar parameter, i.e., the working/intake air ratio, which is the ratio of working air (secondary air) flow rate to intake air flow rate.

2.9.2.2 Wet-bulb/Dew Point Effectiveness

The cooling efficiency of an indirect evaporative cooling system depends on the wet-bulb effectiveness, which is defined as the temperature difference between the intake and supply air divided by the temperature difference of the dry bulb and wet bulb of the intake air, as shown in the equation below:

$$\varepsilon_{wb} = \frac{t_{db,1} - t_{db,2}}{t_{db,1} - t_{wb,1}} \tag{2-2}$$

Where,

ε_{wb} is wet-bulb effectiveness

$t_{db,1}$ is the intake of primary air dry-bulb temperature, ^{o}C

$t_{wb,1}$ is the intake of secondary air wet-bulb temperature, ^{o}C

$t_{db,2}$ is the product air dry-bulb temperature, ^{o}C

Dew point cooling systems can deliver supply air that is lower in temperature than the wet-bulb temperature of the primary intake air, near its dew point temperature. In this condition, the dew point effectiveness can be defined as:

$$\varepsilon_{dp} = \frac{t_{db,1} - t_{db,2}}{t_{db,1} - t_{dp.1}} \tag{2-3}$$

Where,

ε_{dp} is dew point effectiveness

$t_{dp,1}$ is the intake primary air dew point temperature, ^{o}C

2.9.2.3 Cooling Capacity

The cooling capacity of an evaporative cooling system depends on the source of the intake air for the system, which could be either indoor or outdoor air. When the intake air of the system is sucked from indoor air, the cooling capacity can be defined as follows:

$$Q_{\text{cooling,r}} = \frac{c_{p,f}\rho_f V_2 (t_{db,r} - t_{db,2})}{3.6} \tag{2-4}$$

Where,

$Q_{\text{cooling,r}}$ is the cooling capacity of the evaporative cooler, W

$c_{p,f}$ is the specific heat of air at constant pressure, kJ/(kg k)

ρ_f is the density of the air, kg/m^3;

V_2 is the air flow rate of the supply air, m^3/h

$t_{db,r}$ is the reference dry-bulb temperature of a room, ^{o}C

$t_{db,2}$ is the dry-bulb temperature of the supply air, ^{o}C

The above formula calculates the sensible cooling of the evaporative cooling system; it does not consider the thermal comfort improvement because there is no moisture addition. Thus, the total cooling capacity of the cooling system, including both latent and sensible cooling, can be estimated using the following formula:

$$Q_{\text{total}} = \frac{\rho_f V_2 (i_{db,r} - i_{db,2})}{3.6} \tag{2-5}$$

Where,

Q_{total} is the total cooling capacity of the system, W

$i_{db,r}$ is the specific enthalpy of the air at room temperature, kJ/kg

$i_{db,2}$ is the specific enthalpy of the supply air, kJ/kg.

In a case in which the intake air comes from outdoor air, the cooling capacity of the system can be calculated using the sensible cooling of the intake air. The following formula, developed by ASHRAE 2000, can be used to define the cooling capacity:

$$Q_{\text{cooling,IA}} = \frac{c_{p,f}\rho_f V_2 \left(t_{db,1} - t_{db,2}\right)}{3.6} \tag{2-6}$$

here,

$Q_{\text{cooling,IA}}$ is the sensible cooling of the intake air, W

$c_{p,f}$ is the specific heat of the air at constant pressure, kJ/(kg k)

ρ_f is the density of the air, kg/m^3

V_2 is the air flow rate of the supply air, m^3/h

$t_{db,1}$ is the dry-bulb temperature of the intake air, ^oC

$t_{db,2}$ is the dry-bulb temperature of the supply air, ^oC

2.9.2.4 Coefficient of Performance

To provide a rating of the efficiency of an air conditioning system, the energy efficiency or coefficient of performance (COP) is described as the ratio of sensible cooling capacity to total power consumption of the cooler, and can include the electricity consumption of the air fan and water pump:

$$COP = \frac{Q_{\text{cooling}}}{W} \quad [94] \tag{2-7}$$

Where,

W is the measured power consumption, W

2.9.2.5 Water Evaporation Rate (Water Consumption)

The water consumption of indirect evaporative cooling systems depends on the air flow, the dry-bulb and wet-bulb difference of the intake air, and the effectiveness of the evaporator medium. In an ideal case, the water consumption or evaporation rate is calculated by multiplying the moisture difference of the inlet to outlet of the secondary air by the secondary air mass flow rate, then dividing this by the density of water, as illustrated in the following formula:

$$V_w = \frac{1000V_3\rho_{w,f}}{\rho_w}\,(w_3 - w_1) \qquad (2\text{-}8)$$

Where,

V_w is the water evaporation rate, l/h

V_3 is the secondary air flow rate, m^3/h

$\rho_{w,f}$ is the secondary air density, kg/m^3

ρ_w is the water film density, kg/m^3

w_1 is the inlet moisture content of the secondary air, kg/kg (dry air)

w_3 is the outlet moisture content of the secondary air, kg/kg (dry air)

2.9.3 Overview of the Related R&D

Duan et al. [102] studied a regenerative counter-flow indirect evaporative cooler. A thin aluminium plate was used to separate the wet and dry channels, and the wet channels were covered from inside by a porous fibre layer to improve wettability and retain water. The thickness of the whole plate was 0.25 mm. Duan [103] also studied a novel counter-flow dew point cooling system, in which a new polygonal-sheets-stacked heat/mass exchanger made of aluminium coated with hydrophilic cellulose fibre evaporative material was used. This provided the heat exchanger with higher thermal conductivity and water retention/absorption, as well as adding strength to the heat exchanger. Duan reported that fibres glued to aluminium were better than press-heated fibres. Generally, Duan found that: 1) the thermal conductivity of the sheets and the thickness of the materials had a direct effect on the resistance of thermal conduction; 2) wetting the surfaces of the selected materials in the wet channel should have good capacities for water absorption and retention, and 3) materials that are selected should be strong enough to form the construction of the heat exchanger.

Zhao et al. [104] investigated and compared the material effect of a heat and mass exchanger on indirect evaporative cooling. Several materials were tested and studied, such as zeolite, ceramics, fibres, and metals, which have the potential for use as plates in forming heat exchangers. The most adequate materials and structures were identified, and it was reported that the water-keeping capacity (porosity) and thermal property (conductivity) of the chosen materials had a smaller effect on the system's heat transfer and, for the reasons already mentioned, the two parameters had a low impact on material selection. However, durability, shape-holding ability, and waterproofing compatibility had a much more important role in the selection of materials. The study found that aluminium or copper from the metal side with a wick (grooves, meshes, whiskers and sintered) were the most preferred materials. Copper is more expensive than wick-attained aluminium sheets and, therefore, aluminium is preferred for use in the application. Duan et al. [19] conducted a test and studied the potential of a new counter-flow indirect evaporative cooler and its application in China. They set the dimensions for both wet and dry channels at 90 cm in height and 31.4 cm in width, the channel gap between the plate sheets set at 6 mm, with a plate thickness of 0.25 mm, it made of cellulose blended fibre glued with hydrophilic adhesive to the aluminium film, giving the plate a higher wicking performance. Figure 2-14 shows the fabricated evaporative cooler in the laboratory.

Figure 2-14: Fabrication and performance evaluation of a regenerative evaporative cooler [89]

In summary, Aluminium is the most suitable material for plates, because it gives strength and rigidity to the structure of the heat exchanger, it has a good thermal conductivity of 244 W/m.K [105] cheap and widely available. The cover material of the wet channels should have good capacities of water absorption, be wickable, porous and durable.

Cui et al. [106] theoretically studied the performance and design of a counter-flow indirect evaporative cooler closed loop. The researchers confirmed that the air could be cooled to below the ambient wet-bulb temperature and approach the dew point temperature. Their work was validated and compared with experimental work done previously and showed a good agreement with the experimental findings; the validated model was then used to study the effect of employing the room return air as working air in the channels using ribs in the channels. The channel length was pre-set to 1 m; however, it was suggested that the length of the channels should not be less than 200 times the working channel gap (which was 3 mm) and the product channel at 6 mm with 0.2 mm for the plate thickness. The simulated results showed the wet-bulb effectiveness of between 122% and 132% and the dew point effectiveness ranged from 81% to 93%.

Changhong et al. [107] numerically investigated an M-cycle cross-flow heat exchanger with an indirect evaporative cooling heat and mass exchanger. A finite element method was used to address the mathematical model's governing equations for the heat transfer between the wet and dry channels (working air and product air) and the model was validated by published experimental data. The researchers recommended that the average air velocity in the dry and wet channels should not exceed 1.77 m/s and 0.7 m/s, respectively. They concluded that the geometric sizes of the channel, such as length and height, had a significant impact on the performance of the system. A longer channel and a smaller channel height increased the system cooling effectiveness but decreased the COP of the cooler. They recommended a 4 mm channel height and the channel length/height ratio to be in the range of 100 to 300.

Xu et al [108] investigated the energy performance of a novel irregular heat and mass exchanger for dew point cooling. They used computational fluid dynamics (CFD) software to identify the flow-resistance factors of different elements inside the wet and dry channels of the heat exchanger. They summarized that the optimum height of the channel was 5 mm and the length in the range of 1-2 m. The COP of the dew point cooler with an irregular exchanger was 29.7-33.3% higher when compared with a flat-plate exchanger.

Duan et al. [109] studied the fabrication and performance of a compact evaporative cooler and found that the geometric dimensions were linked and had limits. The study showed that the fan power consumption declined dramatically with a channel number of 100-600. The optimum number of channels for low energy consumption and within the limited geometric boundaries was 320 channels for a heat exchanger of 1.08 m depth, so the optimum channel gap was taken to be 3.0 mm. Riangvilaikul et al. [110] investigated a novel dew point evaporative cooling system based on the analysis of the parameters that influence system performance. They found that to obtain a wet-bulb effectiveness greater than 100%, the system should be operated and designed as follows: intake air velocity below 2.5 m/s, the channel gap should be less than 5 mm, the channel length greater than 1 m, and have a working/intake air ratio of around 3.5-0.6.

In summary, simulations and experimental work have been conducted to specify the heat exchanger's channel gap. Simulations were used to test the most effective gap within the limited channel of the heat exchanger and were supported by experimental work to confirm the selection. The channel gap has a link to the length of the cooler directly as well as to the (height of the cooler), which should be within the range of 200-300 times the channel gap. The optimum channel gap is in a range of 3-5 mm. The most effective length of the channel is in the range 1-1.2 m.

Riangvilaikul and Kumar [111] studied a novel dew point counter-flow indirect evaporative cooling system. The researchers concentrated on the air outlet condition and system effectiveness in different conditions (velocity, humidity, and temperature), to cover areas with dry and humid climates. The system was constructed and tested with a 5 mm channel gap and a working/intake air ratio of 0.33. The system recorded wet-bulb effectiveness of between 92% and 114% and the dew point effectiveness ranged from 58% to 84%. The effectiveness of both the wet bulb and dew point was nearly constant, at about 102% and 76%, respectively. They reported that with a channel velocity of around 2.4 m/s, the outlet air temperature recorded was below the ambient wet-bulb temperature and approached the dew point temperature of the ambient inlet air. A formula was extracted from the test and supposed to be correct for the humidity between 6.9 and 26.4 g/kg and a dry-bulb temperature of 25-45 °C with a 0.33 working/intake air ratio.

Zhao et al. [112] numerically investigated a novel counter-flow heat and mass exchanger for dew point indirect evaporative cooling systems. The researchers analysed the important parameters affecting the heat and mass exchanger. It was concluded that the wet-bulb efficiency and dew point efficiency of the heat exchanger largely depended on the dimensions of the HMX's air flow passage air velocity and the working/intake air ratio. They recommended that the air ratio should be approximately 0.4, the velocity

0.3-0.5 m/s, with a 6 mm channel height, giving the condition that the length of the cooler should be around 200 times the channel gap. Duan [101] conducted a comprehensive investigation of a novel counter-flow dew point evaporative cooler and also investigated the working/intake air ratio. When the ratio rose from 0.2 to 0.6, the wet-bulb effectiveness increased, and the outlet temperature dropped from 23.5 to 19.7 ˚C. It was said that the air ratio should be set between 0.4 and 0.5 to achieve the highest cooling capacity and effectiveness, as shown in Figure 2-15.

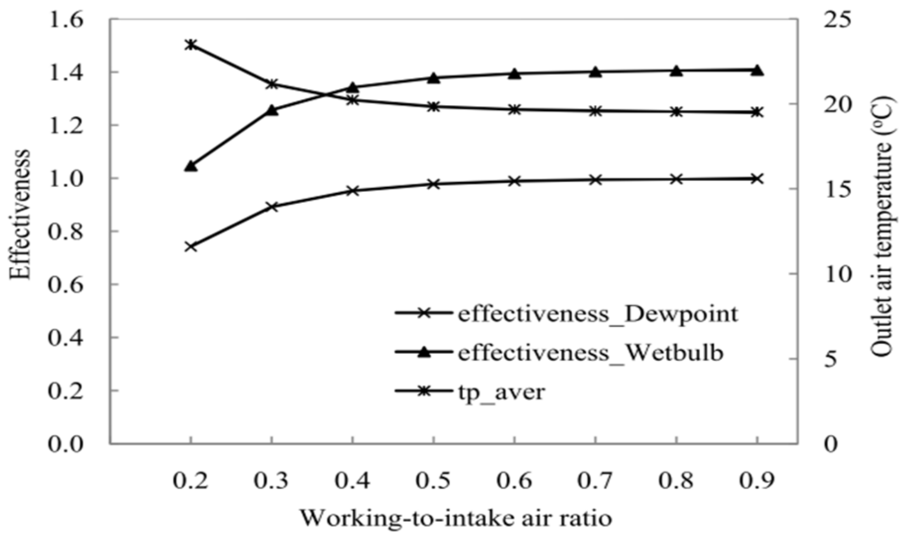


Figure 2-15: Relation between effectiveness and air ratio [87]

Pandelidis et al. [113] investigated the performance of a counter-flow indirect evaporative cooler by analysing numerical data and comparing the different types of counter-flow air heat and mass exchangers: a typical counter-flow unit that works as a heat recovery exchanger, and a novel modified exchanger used to investigate the impact of the location of the holes in the channel plate of a regenerative air HMX. The characteristics and dimensions of the HMX unit used in the study were as follows: 0.7 m in length, 0.5 m in width, a channel gap of 3 mm, a primary air flow velocity of 3 m/s, and a working/intake air ratio of 0.5.

Pandelidis et al. [114] carried out a numerical investigation of three units of a highly efficient and advanced cross-flow indirect evaporative cooler. The performance of the three units of the HMX of an advanced indirect evaporative cooling system was tested. The performance of the HMX flow arrangements was tested, as well as a comparison made of the new arrangement with the original or classical M-cycle indirect evaporative cooler. The physical characteristics used in the study were as follows: the length of the dry channel in the HMX was 1.0 m, the width of the HMX was 1.0 m, and the channel height was 3.0 mm. The researchers established that the inlet part of the heat exchanger and the working/product air ratio had a strong influence on the cooling performance and capacity of the unit.

Su et al. [115] studied the super performance of a dew point air cooling system, which was set to an air ratio of 0.44 for various climates, the product air flow rate was set to 750 m^3/hr and the discharged air to 600 m^3/hr. These values are the same air ratios as the Coolerado M30 Cooler. Later, they investigated the air ratio, which increased from 0.268 to 0.364 when the cooler achieved a maximum temperature drop of 19.1 °C and a cooling capacity of 4.75 kW. They specified the optimum working air ratio as 0.364. Pandelidis et al. (2015) [116] numerically investigated and compared a counter-flow regenerative indirect evaporative cooler HMX with different perforation locations. They recommended that the working/primary air ratio should be kept between 0.3-0.45, as efficiency reduced when the ratio was above 0.47 for the arrangement studied. Cui et al. [117] carried out a numerical simulation to assess a novel efficient dew point evaporative cooler and used ANSYS CFD to predict parameters affecting the performance of the cooler, using different velocities from 0.3-4 m/s. They reported that the optimum velocity was 1.5 m/s and that the channel length should be no less than 200 times the channel height.

In summary, the optimum operation parameters based on the above reviews are as follows: the working/intake air ratio should be in the range 0.3-0.5, and the optimum velocity in the range of 1-3 m/s.

De Antonellis et al. [118] investigated a cross-flow indirect evaporative cooler to assess and reduce water consumption through the experiment. More than 112 tests of different working conditions were carried out in the data centre and found that performance was based on the number and sizes of the nozzles wetting the plates and the water flow rate. Duan [101] calculated the water evaporation rate for a dew point indirect evaporative cooling unit and concluded that the water evaporation rate varies with the weather and regional conditions. Water consumption for the model was in the range of 2-2.5 L/kWh of cooling output. A large list showing the water consumption for Europe and China was produced based on the investigation Duan carried out. Shahi et al. [119] studied water consumption and the re-use of grey water in evaporative cooling to reduce consumption. The study showed that evaporative cooling could provide comfort in relation to 69% of the world's cooling needs. The consumption of water was between 200-650 L/household/day for different sizes of home and there is the potential to reduce grey water in the range 40-100% for evaporative cooling. According to a report on the performance of the Coolerado dew point cooling system [120], the system has a water consumption of 2.5 gallons/ton/hr. Water and energy consumption were used as factors to calculate the payback period, which was found to be between 7.62 and 41.8 years depending on the units and facilities. The annual energy saving was 63% when the Coolerado dew point cooler was compared with the minimum roof top unit.

In summary, indirect evaporative cooling systems are a promising type of cooler that could provide comfort cooling to buildings and their occupants. The amount of water a unit can consume varies and depends on a number of geometric parameters, such as length, width, and channel size, and operational parameters, such as the primary/secondary air ratio, channel air velocity, as well as the climatic conditions of the location and the percentage of air returned from the building to the unit. These parameters decide the water consumption of a unit as each location is different, which is why water consumption can only be compared case by case. Table 2-8 shows some of the related researches and approaches about the dew point cooling system; more researches and investigations are illustrated in Appendix B.

Table 2-8: Dew point cooling previous research works

Author	Zhao et al [112]	Franko [121]	X Zhao [122]	B. Riangvilaikul [123]	G Heidarinejad [124]	Ala Hassan [125]& [126]	AE Kabeel [127]	Stefano [128]
Year of study	2008	2011	2009	2010	2009	2010 & 2012	2016	2016
Type of study	Numerical & simulation	On-site experiment	Analysis & evaluation	Simulation & lab experiment	simulation & Lab Experiment	Analyse & theoretical investigation NTU	Numerical and experiment	Experiment
Method	Simulation	Domestic & commercial application	Application	Experiment	Experiment	Simulation	Investigation & experiment	Investigation & experiment
Cooler Flow type	Counter flow	2 different cooler test IDEC Counter flow	Counter flow	Counter flow	Indirect -direct	Single & 2 stage IDEC Counter flow	Counter flow with baffles	Cross flow
Test Parameters **Air ratio** **Inlet temp** **Dew point temp** **Air velocity** **Humidity ratio**	 0.5 28 16 1 m/s -	 DB 40.3-22.5 C WB 19 C - 8 g/kg	 6 china cities covered (different weather analysed) for 2KW system RH 70%	 0.33 25-40 C 2.4 m/s 7-26 g/kg	 DB 27-49 C WB 15-33 0.59 m3/s 10-95 %	 0.7 34 C 12.2 C 0.68 m/s 9 g/kg (34%)	 0.1-0.6 35 C 1.5- 5.5 m/s 14.5 g /Kg	 30-35 DB 20 WB 3.7-5.7 m/s 10 g/kg

Outlet conditions **Dew point Eff %** **Wet-bulb Eff %** **Water cons** **Average EER** **Outlet temp** **Saving** **Cooling output**	0.9 1.3 - - -	Ave 0.65 and 0.75 Ave 1.06 and 1.24 7.2-11.5 Daily out Ave 10.2 C 52-56%	2.6-3 litre/kWh 2 kW (test)	0.58-0.84 0.92-1.14 - - 15.6-21.1 C -	30.5 66-68 %	1.16	0.75 – 1.36 (5 configuration 0.24 kg/hr - NK NK	0.50-0.85
Cooler Sizing **Length** **Width** **Channel gap** **Plate thickness** **No of channels**	1 m N/K 10 mm	- - -	N/K -	120c m 8 cm 5 mm 20 wet + 19 dry	50 cm 50 cm 7 mm 0.3 mm Height 40 cm	50 cm 50 cm 3.5 mm 0.5 mm 1 mm (water film)	120 cm 10 cm 5mm-buffles 0.5mm cot+Al 20 wet 19 dry	50 cm 47 cm 3.35 mm 0.14 mm 119 plates
Recommendation **Size** **Chanel height** **Air velocity** **Length** **Work/intake ratio** **Reducing velocity** **Water temp**	- ≤6 mm 0.3-0.5 m/s 200* height 0.4 (max effect) 100% cost increase Little effect	Dew point can supply air temp comparable to refrigeration systems -	- -	- - - - - -		IDEC could drop DBT below the dew point Using Epsilon NTU method	Working/ Intake Air=0.3	Higher velocity leads to high evaporation Counterflow is better outcome than crossflow in terms of the water division

2.10 Cooling Load

Heating and cooling load calculations are the primary steps in designing air conditioning. The calculations affect all the parts involved in the design, such as piping, ductwork, diffusers and fans, and system sizing. The proper calculation of the load could also reduce capital cost. Cooling load is the energy input to remove the internal heat to maintain comfortable conditions and the desired internal temperature, as required. The amount of cooling and heating required in a building varies according to the time and depends on internal and external factors. Cooling load is the product or combination of several parameters at the same time, such as convection, conduction, and radiation heat transfer processes through the building shell. The heat sources of a building are:

- External, such as the roof, walls, windows, ceilings and internal partitions.
- Internal, such as the occupants, lighting, and any equipment used in the building.
- Infiltration, which is unwanted air leakage through openings.
- The air outside the system, ducts, reheating, pumps and fans.

The following are methods used to calculate residential cooling loads.

Heat balance (HB) [45]: In this method, the load is calculating surface by surface for each of the convective, conductive and radiative zone surfaces, then the heat balance for each zone or room. The load is calculated directly, and no arbitrary sets of parameters are involved in the calculations.

Radiant time series (RTS): This is a simplified method originally derived from the HB method of performing cooling load design calculations. This method replaces the non-heat balance method, such as the transfer function method (TFM), cooling load temperature difference (CLTD) factor, and the total equivalent temperature differential method with time averaging (TETD/TA).

Residential building loads are categorized with certain characteristics that distinguish them from other cooling load patterns:

- Small internal heat gains from occupants, lighting and equipment.
- Varying space usage and flexibility of zone usage within the building and temperature change is tolerable.
- Smaller zones mostly dealt with as one zone and one temperature setting.
- Larger distribution losses: this occurs more in Western buildings, where ducts are installed in unconditioned zones such as attics.
- Partial loads: most residential building loads are between 5-18 kW for cooling. Systems are normally designed to cover the worst day scenario, and for the rest, the systems operate at partial loads most of the time. That is why oversizing a system harms good system performance.

An accurate cooling load calculation is vital in terms of sizing and energy consumption. When properly sizing a residential building that comprises multiple zones, each zone has to be calculated separately and sized according to its peak. If the building is conditioned using a central provider, the load is the sum of all the loads [59], while in multi-family units, such as flats, each apartment has a zone load which is the summation of a load of all the zones in the apartment with a separate system. Mui et al. [129] used a new mathematical model to generate time-irregular occupant load patterns using the Monte Carlo sampling technique as the basis for calculating cooling load variations. By mixing the time-varied occupant-load profiles, the difference in cooling load capacity was seen to vary from 1% to 5%. Although the study was used for office buildings in Hong Kong, it should be possible to apply it to other buildings and different kinds of properties.

The peak cooling load is occasionally assumed and calculated at the early stages of a project. Uncertainties affect input data, such as a lack of information input, and sometimes the uncertain information is large enough to mislead or cause the results to vary dependent on the assumptions. Air conditioning engineers deal with this problem by taking the worst case or by taking large safety factors. For example, Munoz et al. [130] investigated the uncertainty in peak cooling load calculations and proposed a new solution based on stochastic simulation methods. In this method, a case study is taken as an example and all the data needed for the simulation and its output. In this case, the decision is based on the output analysis of the load with some risk-taking concerning the ultimate cooling design by the building owner as shown in Table 2-9. The researchers stated that a slight change in the peak cooling load per unit surface could cause a significant increase in the investment in the case of a larger chiller being required. Consequently, the more energy required, the greater increase in the secondary element costs, such as a larger steel structure and more ductwork. Thus, the decision-maker can balance risk and cost before choosing a larger plant.

Table 2-9: Cumulative probability of selected peak cooling load levels [130]

Peak load (W/m^2)	Cumulative probability
74.3 (min)	0.00%
75	0.20%
80	4.20%
85	25.60%
88.3 (mean)	50.00%
90	63.20%
95	91.20%
97	96.40%
99	98.60%
100	99.60%
102	99.80%
102.8 (max)	100.00%

Mohamed et al. investigated the effectiveness of high reflective roofs in minimizing energy consumption in residential buildings in Iraq [131]. Iraqi residential buildings consume a very large portion of energy, 48% of the country's total electricity production is used by residential buildings. This work investigated minimizing cooling load through covering the roof of a two-storey building with 45% reflective material compared with the ordinary roof finish. The total building annual consumption was reduced by 73% through covering the roof with highly reflective materials, such as solar reflectance SR 0.8 and thermal emittance TE 0.9. The researchers set the internal temperature for an Iraqi residence to 25 °C. The city of Yuma in Arizona was selected to represent Baghdad for the simulation for having a similar climate condition and the cities lie almost on the same latitude line. Al-Ragom [132] investigated retrofitting a Kuwaiti residential building to save energy by reducing the cooling load and took a two-storey building as a case study. Various cases were developed to represent possible retrofitting scenarios. It was proposed that if residential buildings were to be improved, it would lead to a reduction in energy consumption worth savings of $577 million US dollars in 10 years' time.

Hatemipour [133] studied the cooling load power consumption during summer in Iran (a hot and dry climate). Consumption is at its highest in July and August. Three different housing models were investigated, together with a hospital and a trade centre. Using a light colour on the external walls, a roof with insulation and double glazing would decrease the cooling load by 40% and lead to an annual saving of more than 60% in peak times. Shariah et al. [12] investigated and calculated cooling and heating loads for three different locations in Jordan. The cities of Irbid, Amman and Aqaba were tested, with the following outcomes: 1) ceiling insulation reduced cooling and heating load in a mild and hot climate; 2) heating and cooling load were reduced by 44% when both the walls and roof were insulated; and 3) in a mild climate, insulating only the walls affected heating load, while in a hot climate, such as Aqaba, it affected the heating and cooling load.

In summary, cooling load is the summation of the effects of external heat gain and internal heat gain on a building. The heat gains in residential buildings are small. Load calculation for any building is the first step in cooling system design. The selection of an appropriate cooling system that provides comfort for the occupants is vital, but oversizing should be avoided because it affects the capital cost and energy consumption. Residential building loads are relatively small, although some designers are designing the equipment according to the occasions of the peak load in the early stage of a project.

2.11 Economic and Environmental Analyses

Considering the economic aspect of any project is vital, especially in terms of investments and contracts, so, in addition to studies run for the technical improvement of cooling systems, the economic element should also be considered in parallel. For IEC cooling systems, it is important to consider electricity and water consumption; for some other coolers, only the electricity consumption is the main parameter of economic studies; and in others, the capital and maintenance costs must also be kept in mind. Economic investigations should also be carried out, such as the payback period. In terms of environmental issues, the carbon emission capacity of the system needs to be calculated to establish if it meets the requirement of achieving low carbon energy targets.

With regard to feasibility studies, conventional systems could be replaced with innovative ones to demonstrate the viability of the new system in a particular climate. This could be achieved by assessing the capability of the system to provide a good level of thermal comfort, the accessibility of the water source (for IEC) and the economic cost of the system.

2.12 Chapter Summary

A critical review of residential building fabrication and cooling systems in hot and dry climates was carried out in this chapter. The results of the review help in understanding the key energy-related parameters of building fabrication and the status of common cooling systems and their acceptance in a hot and dry climate. The review helped to understand the current status of the new dew point system and its technical development and identify the potential of its application in such a climate.

Building fabrication has a direct effect on the energy consumption for cooling in buildings. Polystyrene is one of the most effective insulation materials in buildings, as even only insulating the walls could save over 30% of the energy consumed for cooling. Clay bricks were used in the past but are now being replaced with concrete, as good insulation is the most effective way to tackle the problem of high thermal mass. U-values also have a direct effect on the energy transmitted into a building, as the smaller the U-value, the more energy-efficient the construction. U-values are different in each country, regardless of the type of assembly. Developed countries have very low U-values set because of energy-saving challenges. Concrete, stone, and brick have high U-values, but insulation has a very low U-value.

Glazing also affects the cooling load. The best window/wall ratio is 10% in hot and dry climates and 20% for moderate climates. Clear double glazing alone does not reduce cooling load, but low-emissivity glazing with external shading reduces the solar heat gain.

Low emissivity glazing is effective by the coating on the external surface which controls the solar heat gain into the building by reflecting the long-wave infrared energy (heat) and letting the lighting through, and low emissivity glazing works as a window insulator. External overhang generally provides shading over the windows and minimizes the direct solar admissions through the windows.

Building orientation must also be considered when designing windows. Each country has its building codes to achieve high energy saving, the codes depending on the climate and traditions of the country.

In addition to building fabrication, the heat generated by the human body affects the cooling load of a building and depends on the activity in the building, air movement, and humidity. Equipment is another heat source in buildings and has a large impact on cooling load. The heat generated in a building depends on the quantity and quality of the equipment. For example, using energy-efficient equipment and LED lights would lead to a decreased load inside a building. While occupants' activities cannot be changed, increasing air movement could improve the amount of heat generated by human bodies.

Indoor air conditioning and air quality are health-related, so it is important to consider these as people spend around 90% of their lives in buildings. Each person needs 2.5 L/s of fresh air with a relative humidity of 40-70%. Comfort differs from one person to another at the same time and in the same environment. In summer, 24-26 °C is the temperature set for comfort, but the comfort level limit could be higher with increased air velocity and relative humidity.

Conventional cooling systems, such as split air conditioners, could be efficient and acceptable to the public but consume a high rate of energy. Thus, it is a good idea to replace them with economic and environmentally friendly systems, such as the dew point IEC. The latter is a promising type of cooler that can provide comfort cooling to buildings and occupants and consumes less energy in comparison with conventional coolers. The water consumption of the cooler depends on geometric and operational parameters, as well as climate. The optimum parameters of the latter are specified in this review. Aluminium is the best material for the heat exchanger plates of a cooler. The length of the heat exchanger should be within a range of 200-300 times channel gap. The optimum channel gap is in the range of 3-5 mm, and the optimum length of the channels is 1-1.2m. The optimum operational parameters of the cooler are as follows:

the working/intake air range is in the range of 0.3-0.5, and the velocity is in the range of 1-3 m/s.

Cooling load is the basis for the choice of the cooling system and, to save energy, it should be as low as possible for any building. Cooling load is the summation of the effects of external heat gain and internal heat gain on a building. Building fabrication, climate and the resident(s) are the main parameters that affect cooling load. Finally, for any project, the cost should be considered. In each step of the current study, such as the fabrication of the building, calculation of cooling load, and design and fabrication of the new dew point system, cost played a main role and was taken carefully into consideration; thus, saving energy means saving both money and the environment together.

2.13 Knowledge Gap

The literature reviews showed a clear impact of building interventions on the cooling load reduction, consequently, on the energy-saving to some extent.

The previous research investigations regarding the newly developed dew point coolers are mostly laboratory-based investigations or performance test based.

A real weather data is vital to be involved in the simulation of the system, to assess the feasibility of it in a location's climate and to assess the system, as the bulkiness and the real size of the new system, which is a constraint for usage in some places.

The literature review reveals a clear gap and a connection between the building load and fabrics with the new developed indirect evaporative cooling system. This research tries to combine the hourly building-cooling load, which required for sizing a system, with the hourly cooling output of the dew point cooling system using real weather data.

This study would be conducted for a location like Erbil, Iraq. Buildings have never been studied before, in terms of construction, materials or intervention, and nor introduced to such a new system, like dew point evaporative cooler with low energy consumption. The details of that would be in chapter 3.

Chapter 3: Context and Case Studies

3.1 Chapter Introduction:

A critical review of the case studies is presented in this chapter. The aims can be briefly specified as follows:

Give a review of the chosen area and city (Erbil) with regards to the location and climate conditions, especially in summer.

1- Represent the state of the area with the rapidly increasing urban prosperity and expansion, and housing shortages. Also, the political impact on this aspect.
2- Description of energy and water resources, demand, and consumption, including the energy and water shortage, due to the rapid growth of the city
3- Demonstrate the change in building typology and fabrication during the city's recent history and their impact on energy consumption, especially on cooling systems, and then describe the accompanying problems due to the absence of a standard building code.
4- Give an illustration of the widespread cooling systems in the area.
5- Identify the case study building, clarifying the reasons for choosing them.

3.2 Erbil: Location and Climate Conditions

Iraq is located between the latitude of (37.18-29.97°) North and a longitude of (40.28-47.97°) East, has a mostly arid climate, and hence frequently experiences temperature extremes. It has been experiencing more summer heat waves in recent years due to the effects of global warming. The country has two main climatic seasons, a hot and dry summer that continues from June to September, and a cool and wet winter that lasts from November to March. The mean maximum temperature in summer can be as high as 41-45°C in the country's more southern regions but becomes more temperate toward the North, typically ranging between 27-31°C. In winter, the mean minimum temperature falls to around freezing in the Northern region. Rainfall is less than 100 mm per year in the southern and central desert areas but can be around 1000 mm per year in the mountainous areas in the North. Around 90% of the rainfall occurs between November and April, with the rest of the year remaining tremendously dry. Hence, a large part of Iraq is considered to be desert due to the lack of rainfall and extremes of temperature. The temperature increase in Iraq is occurring much faster, especially in the Northern regions (Kurdistan), in comparison to the global average increase in temperature [134].

Kurdistan, as a region, is representative of the north of Iraq, and its capital is Erbil, as shown in Figure 3-1, Kurdistan's climate is semi-arid. Summer is very hot and dry and extends from June to September, but hot extremes mostly occur in July and August, but rarely reaches 50°C. The mean high temperature is between 39-43°C. Autumn in Kurdistan is dry and mild with an average temperature range of 24-29°C in October, and which then gets colder in November. Winter is cold and wet with a high possibility of snow and frost in cold extremes, especially in its mountainous areas [135].

Figure 3-1: Location of Erbil city within Iraq and Kurdistan

Erbil also called Arbil or Irbil, or even Hawler by Kurdish citizens is the capital and largest city of Iraqi Kurdistan. It is in the north of Iraq, lies about 350 km north of Baghdad and had a permeant population of 2,009,367 in 2015. It is one of the oldest inhabited cities in the world, having seen human settlement since possibly 5000 B.C. [136] The ancient citadel of Erbil is located at the heart of the city; it was occupied until 1970 but was later evacuated because it is recognized as being one of the oldest citadels worldwide by UNESCO. This ancient citadel was built on a 102,000 m^2 area, has an oval shape and has an elevation of 25-32 m above the surrounding plain. It was considered an independent city with markets, schools, mosques, and baths. Erbil has seen circular expansion around the castle over the years, as shown in Figure 3-2. Despite the urbanisation of Erbil over the past few decades, this ancient citadel and its architectural heritage are still well preserved, due to considerable effort on the part of UNESCO and the Regional Government in maintaining the city's historical and cultural heritage. The Hurrians (a Bronze Age people) were the first to establish Erbil, which they called Urbillum, after which they expanded their rule to the remaining Northern parts of Mesopotamia. The city has subsequently been ruled by various regional authorities such as the Assyrians, Arabs, Seljuk, and the Ottoman Turks.

Figure 3-2: Central Erbil in the past (top) and the present (bottom)

Erbil is the largest city in Kurdistan and the fourth largest in the whole of Iraq. The central district of the city is a plain, whilst there is a mountainous area in the north of the city on the border with Turkey and Iran. Erbil is located at 36.2^{o} N. and 44.12^{o} E. Apart from the mountainous area, central Erbil is the hottest city in Kurdistan, but it gradually becomes colder as one moves towards the mountainous area at the north of the city, which is one of the most beautiful tourist destinations in the area. The temperature can reach up to 42-45°C in July and August, whilst the minimum temperature is around 2°C in January [137]. The precipitation and the average annual temperature are 386 mm and 21.85°C, respectively [138]. The vast majority of the rainfall occurs in winter, whereas it remains very dry in the summer months between June and September.

The weather data for Erbil extracted from the EnergyPlus software shows that the extremes of heat occur in July and August and that the relative humidity is extremely low in summer, as shown in Figure 3-3.

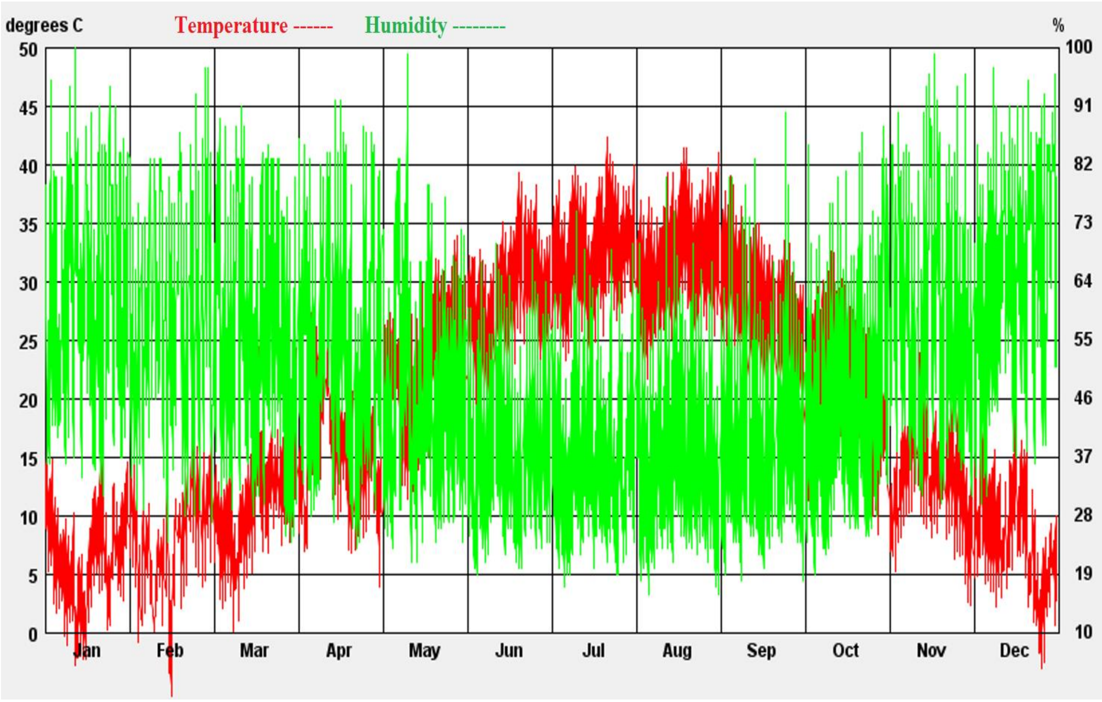


Figure 3-3: Hourly annual dry bulb temperature and relative humidity in Erbil [6]

Over the summer season, the dry bulb temperature is mostly in the region of 20 to 40°C, as the number of hours at which the temperature is between 25 and 30°C can reach as high as 1088 hours during the six months of summer. Extreme temperatures over 40°C occur for the lowest number of hours in summer, as shown in Figure 3-4. These hot hours mostly occur during the daytime, as at night, the temperature drops sharply; indeed, on some days the temperature difference between daytime and night can have a difference as high as 20 °C.

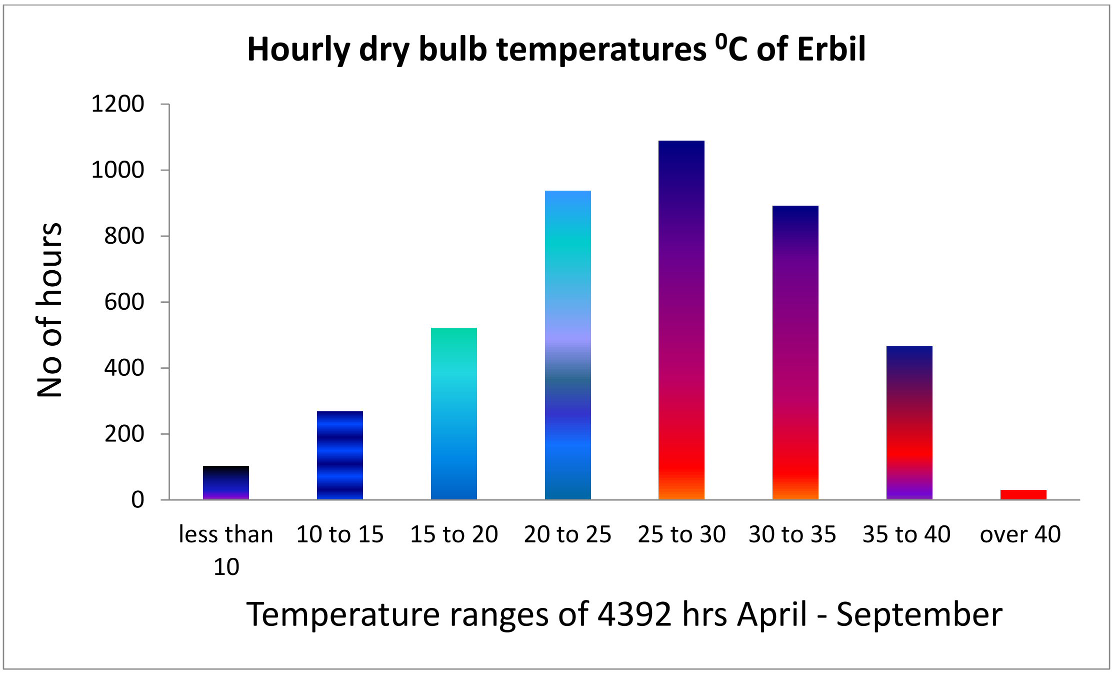


Figure 3-4: Dry bulb temperate hours over summer in Erbil [139]

3.3 Development and Energy Demand

3.3.1 Development of Kurdistan (Erbil)

The Ministry of Municipalities and Tourism within the Kurdistan Regional Government jointly authored the master plan project to develop the city of Erbil. The plan includes guidelines to improve the different districts with applicable community facilities. The master plan would transform the city into a space that would make citizens' daily lives easier [140]. The project is planned to be carried out on a 110 km^2 site area and should be completed by 2030. Figure 3-5 shows the master plan stages announced by the designer company up to 2007 and can be essentially described as a circular expansion around the castle.

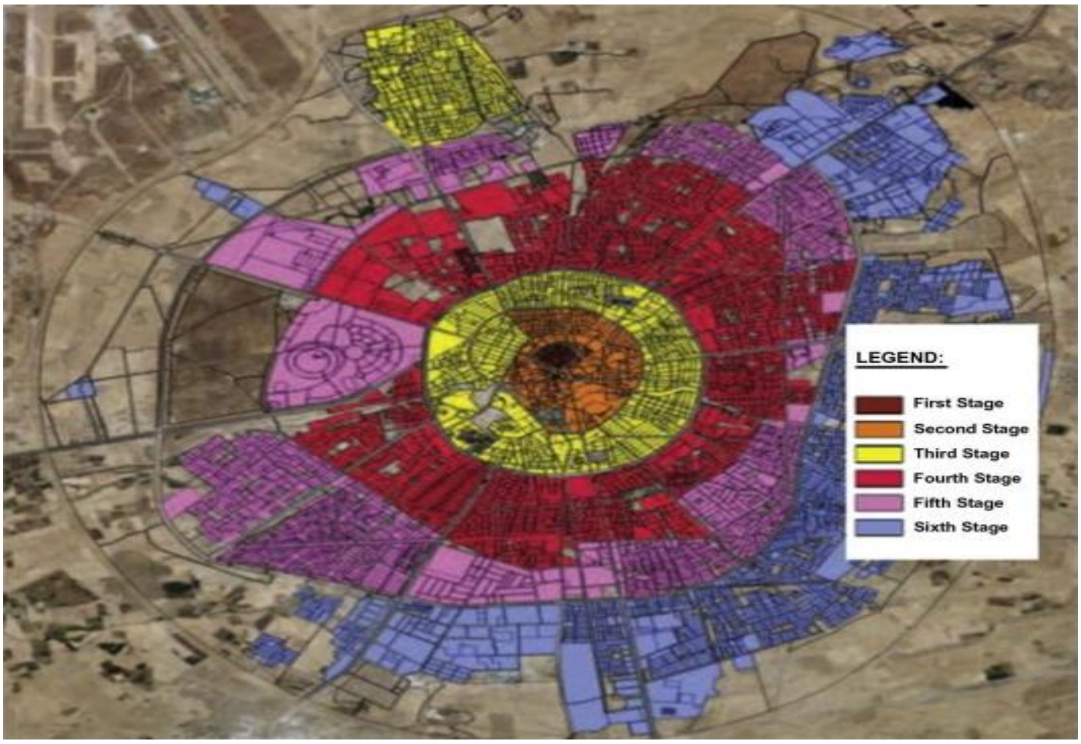


Figure 3-5: Stages of urban transformation of Erbil City up to 2007 [141]

In 2003, there were 78 housing projects with around $5.8 billion of capital and land investment costs, consisting of different types of residential building units, low-rise flats and high-rise flat building projects which have been announced according to the Kurdistan board of investments [142]; some of these dwellings are already sold out and occupied, whilst others are still under construction. Some other projects have recently been licenced by the board of Kurdistan investment in Kurdistan cities, as the majority share goes to the housing sector, consisting of 165 housing projects for the whole of Kurdistan. An intensive survey was conducted to collect information about the residential projects undertaken in Kurdistan, which is listed in Appendix A. Erbil has the largest share of 81 housing projects, followed by Suleymaniyah and then Duhok, where the housing projects are planned for construction on 133 km^2 of land [143], as shown in Table 3-1.

Table 3-1: Recent housing projects in Kurdistan, and housing summary [143]

Governorate	Total Land given to projects km^2	Land used for residential housing buildings km^2	Total of housing projects
Erbil	76.38	61.11 (% 80)	81
Suleymaniyah	36.22	17.02 (% 47)	47
Duhok	19.88	7.55 (% 38)	37
Total	**132.5**		**165**

3.3.2 Energy Resource and Consumption

The boom of the Kurdistan Region in the last few decades has had a considerable impact on energy consumption. Until 2007, Kurdistan was producing only 482 MW of electricity from the hydropower at Dukan and Darbandikhan [144], but even at that time, this figure was much less than the demand. To cover the difference, the Kurdish government imported large gas and diesel turbine generators which produced and supplied energy to certain areas of Kurdistan [145]. As the associated fuels were produced in Iraq and were given for free by the government, the price of electricity was very low in Iraq generally, including in Kurdistan. The price of electricity is one of the cheapest in comparison with the surrounding countries. The electricity tariff per kWh in Erbil is nominal and can be as low as \$0.058 [146]. The government spends \$3 billion on electricity per annum according to the Kurdish Prime Minister, Nechirvan Barzani [147]. The energy in Kurdistan has a fixed nominal price, and consequently, citizens' electricity usage is largely uncontrolled. Electricity in the region is used for heating and cooking, and the high electricity usage at peak times in summer devoted to cooling leads to regular power outages. Up to this point in time, Kurdistan has a total electrical capacity of 1480 MW, as shown in Table 3-2, to which 355 MW are additionally imported from Iran and Turkey to cover any power shortages [145]; however, this still does not cover the peak demand of 2128 MW. According to the Ministry of Electricity for the region, Kurdistan is in total producing between 2700-3000 MW electricity, while demand in the region has risen to 3500 MW. To date, the Kurdish government has spent \$1.5 billion on the energy sector. The above figure represents a prediction of total energy usage in Kurdistan, while at the same time, a statement from the Ministry of Electricity indicated that Kurdistan needs 3500 MW of electricity [148]. The energy demand increases with the completion of the investment building projects as these buildings occupied with time, so new power plants are required to cover the associated power gap. The Kar Group [149] and ENKA are currently working in the power sector to provide Kurdistan with new power plants [150].

Table 3-2: Electricity produced from existing power plants in Kurdistan [133].

Existing Power Plants	Type	Max Capacity MW	Maximum Available Capacity-MW									
Exisitng Plant and imports		**Total**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2020**	**2025**	**2030**
Dokan	Hydro	400	400	400	400	400	400	400	400	400	400	400
Darbandikhan	Hydro	249	166	166	249	249	249	249	249	249	249	249
Erbill IPP	GT	500	500	500	500	500	500	500	500	500	500	500
Import from Iraq	Import	200	100	100	100	100	100	100	100	100	100	100
Import from Turkey	Import	155	155	155								
Import from iran	Import	200										
Tasluja	Diesel	50	50	500	50	50	50	50	50	50	50	50
Erbil 29 MW	Diesel	24	12	12	12	24	24	24	24	24	24	
Suleymaniya 29 MW	Diesel	24	12	12	12	24	24	24	24	24	24	
Dohuk 29 MW	Diesel	24	18	18	18	24	24	24	24	24	24	
Erbil 10 MW	Diesel	10	8	8	8	8	8	8	8	8		
Suleymaniya 15 MW	Diesel	15	12	12	12	12	12	12	12	12		
Aqra 10 MW	Diesel	10	8	8	8	8	8	8	8	8		
Suleymaniya (Sakr)	Diesel	81	81	81	81	81	81	81	81	81		
Total Existing			**1522**	**1522**	**1450**	**1480**	**1480**	**1480**	**1480**	**1371**	**1299**	

3.3.3 Water Resources and Consumption

Iraq does not overlook any sea or ocean, but there are two main rivers that pass through the country, the Euphrates and Tigris, which represent its main water resources. Iraq comprises the largest part of Mesopotamia that encompasses the land between the Euphrates and Tigris rivers. The combination of population growth, climate change, limited environmental consciousness, extremely low water tariffs leading to high water consumption and waste are the main causes of water problems in Iraq. Erbil is located in the dry area between two tributaries, the Little Zab and Great Zab, as shown in Figure 3-6; it also shows the main rivers and other tributaries in Iraq.

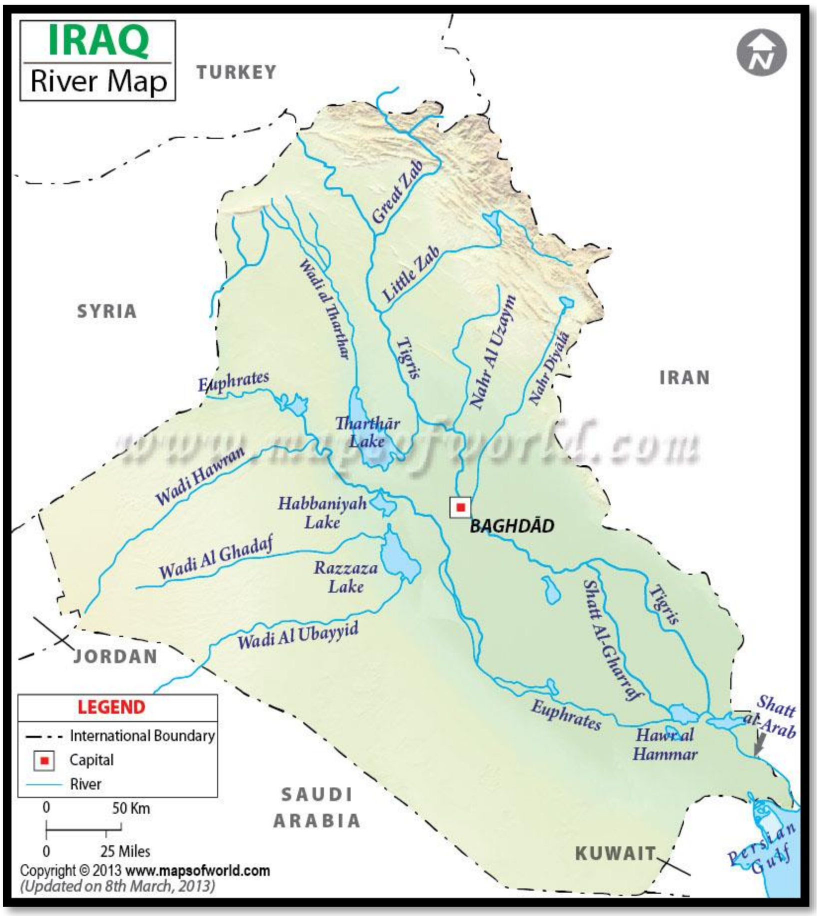


Figure 3-6: Rivers and surface water in Iraq [151]

There are three water treatment plants in Erbil (Ifraz1, Ifraz2 and Ifraz3, and a proposed Ifraz4 project) as shown in Figure 3-7, where the surface water is supplied from the Great Zab for these projects. The first three plants' capacities shown in Table 3-3. The total daily production is 338,400 m^3/day. Underground water is another water resource in Erbil, from which daily production is 262,500 m^3/day.

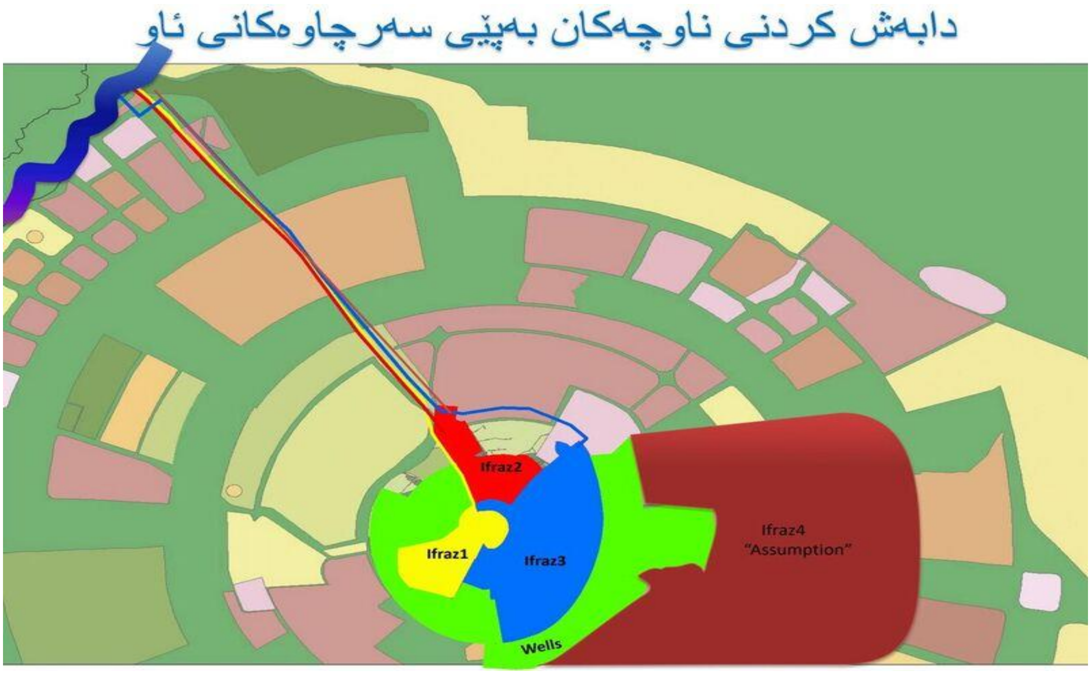


Figure 3-7: Water secretion projects in Erbil [self-reference]

Private water wells are popular in Erbil, where more affluent people maintain them as an extra water resource. According to the World Health Organization (WHO), the water per person rate matches WHO standards and all resources provide drinking water, but it is used for other purposes that are considered a waste of clean water. The cost of water production is \$0.33/m^3, and currently, the nominal water tariff is as low as \$8-13 per house per month, though this depends on the size of the house. Hence, there are no problems associated with a lack of water in Erbil; rather, water management itself is the problem [personal communication].

Table 3-3: Water treatment plant capacities [self-reference]

Water project	Construction Year	Capacity m^3/ hr
Ifraz 1	1968	1800
Ifraz 2	1985	3300
Ifraz 3	2006	9000
Sum.		14100

The lack of awareness about water consumption is a major part of the problem. Figure 3-8 shows that 40.5% of the overall water requirement in Iraq is for the civil sector.

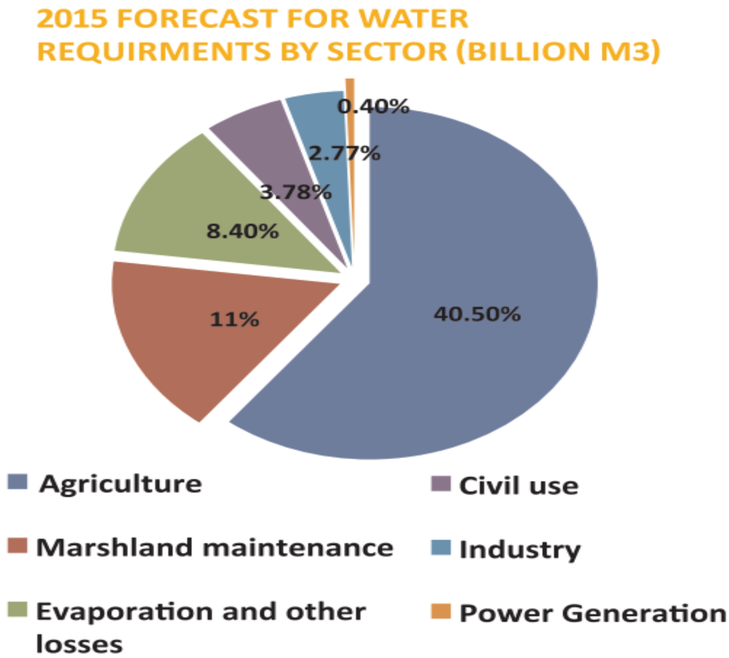


Figure 3-8: Water requirements in Iraq [152]

3.4 Residential Buildings

3.4.1 Historical Review of Residential Building

The design of Iraqi houses (including Kurdistan) changed completely in the late 1950s. Before this date, houses consisted of a courtyard surrounded by other facilities such as bedrooms, kitchen, bath, etc. The houses were either one or two storeys (usually one storey). Some houses had a basement that was used as a store or as a living space in hot summer due to their relatively cool temperatures in comparison with the ground or first storey of the house. If the house was a two-storey building, then the bedrooms would be on the ground floor, with holes in the wall opposite to the main window for ventilation purposes. The material used to construct the main walls was a hay and mud mixture used as a binding agent with stones, and with gypsum plaster covering the interior surface. These houses were open to the air circulation; cooling systems were rarely used as the buildings were comfortable and naturally ventilated.

The more recent residential buildings across the entirety of Kurdistan and Iraq have the same code and design; their construction materials are usually concrete blocks and concrete. Houses (villas) are a very popular residential unit as the development is mostly horizontally. Modern residential buildings in Kurdistan can be divided into three main types: typical houses (100m^2 – 250m^2) with one or two storeys; large houses (over 300m^2) with two storeys; and apartments. Most people live in the first type of building, so houses under 300 m^2 are widespread [153]. Apartments are not desirable, as they are new to the Kurdish culture but have become increasingly popular in the last decade due to the high land prices. As the first type of house is very popular, both local and foreign companies have been encouraged to invest in substantial projects to build thousands of units, resulting in such houses constituting a substantial proportion of private residential buildings.

3.4.2 Housing Shortage

The Iraqi Ministry of Planning and Statistics estimated the Iraqi population to be 33.33 million including Kurdistan, where the latter's population was estimated at just under 5 million people [154]. According to the Iraqi Ministry of Housing's report, with the growth in population, Iraq needs 2 million additional residential units by 2016, so 200,000 units/year should have been built since the report was submitted [155]. The UN-HABITAT conducted a survey in the Northern Iraqi Kurdistan region, where the average number of people per household in Erbil was five per dwelling in the urban area and surrounding towns; this number was slightly larger in Suleymaniyah (second-largest city in Kurdistan) at 6-7 people per dwelling, and in Duhok (third-largest city in Kurdistan) was 10 people per dwelling. Generally speaking, in rural areas, the number of habitants per dwelling is six on average [156]. Also, another UN survey about the residential unit size of a typical house in Iraq showed that the average house consisted of 226.6 m^2 of land with an average building footprint area of around 143.0 m^2, with six people per house unit, and an average floor area per person of 25.7 m^2. This figure is generally taken to suggest overcrowding, here by 5.3% [157].

3.4.3 Building Codes and Materials

Since 1980, Iraq has suffered from several unusual situations, not the least of which has been several wars and internal conflictions that resulted in depression in all sectors. The building is one of the sectors that dropped behind without any updates in either construction assembly technology or the materials typically used. Iraq has never had a set of proper building standards to follow, therefore different materials, construction methods, and designs are followed by non-qualified tradesmen, especially in residential buildings. A document has been prepared called interim Iraqi construction standards (AFCEE) by the Technological University of Baghdad, as shown in Table 3-4, which is still followed in Kurdistan as it is still part of Iraq. The AFCEE document contains all applicable industry standards relating to civil, electrical and mechanical applications and materials required in a building through a construction guide [158].

Table 3-4: Iraqi interim building standard code [158].

Building	Fabrics and Construction Assembly
Cement	• Cement used in Iraqi buildings should be Portland cement, which must comply with the standard of requirement IQS 51984 for cement. Besides, there are some other types of cement, which can be used in Iraqi buildings with a test certificate.
Wall	• Concrete blocks, hollow or filled, should be according to IQS 1077-1985. • The outer mortar cover is cement mortar and is of 2 cm thickness in two coats of rendering, where the second coating applied should comply with Iraqi B.S 1199 standards. • Two coats of gypsum plastering are applied to the interior walls, the first one is to cover and bond with the walls, and where the second coat is the finishing coat, the thickness should not be less than 2 cm. • Bricks can also be used, but not in the north part of Iraq anymore because of being time-consuming to build.
Floor (tiling)	• Iraqi house tiles are normally terrazzo tiles in different sizes, but mainly 30 x 30 x 2.54 cm and 40 x 40 x 3.17cm, which is a crushed marble chip in grey or white Portland cement. This will be added to the concrete floor of sand and cement mixtures, where ceramic tiles for flooring have been introduced into Iraqi buildings, and those tiles should be according to standards R-61-61 and federal specification 55-T-308b, where sizes and colours are selected according to the engineer's requirements and needs. The minimum crushing strength should be no less than 600 kg/cm^2.
Roofs	• Roofs should have a steel bar mesh covered in concrete, where the distance between the steel bars of the mesh is 15 cm square, with 12 gauge thicknesses. • Roofs in all buildings are plain, and concrete should be according to ASTM A82-94. • 2 coats of gypsum plaster no less than 2 cm in thickness.
Doors (internal)	• Internal doors should always be wooden, especially in new standard buildings. They should be properly fixed with the hinges and flushed or painted according to Iraqi standards.

Doors (outside)	• Metal doors and mainly for outside should comply with it should be designed to stop against wind load which is 75kg /m, painted with anti-rust paint and a coat of an oil standard paint P28.
Windows	• Steel windows, although not currently seeing much use, are nevertheless used for windows in some villages or simple buildings. • Aluminium frame and PVC windows are widely used with 4 – 6 mm clear glass thickness. • No standards for sizing windows
Direction	• No standards or requirements for directions

For comparison, Phoenix in Arizona, USA, is at the same latitude as Erbil and has very similar weather. Their construction material and building assembly are very different and there is an obligation on every person and/or company to follow the Construction Law (Construction Code) set by the local authority.

3.5 Cooling Systems in Buildings

Cooling systems were rarely used in Kurdistan until the 1950s, because i) the buildings were cool and naturally ventilated, ii) the absence of any cooling technology, and iii) the weather was generally cooler (no global warming)[159]. The first cooling device was the basic cooling fan, which does not cool the air but creates air flow, and thus can evaporate the sweat on the skin and consequently lower the body temperature. There are three kinds of fans, desk fan, floor-standing, and ceiling fans. Fans are still used in Kurdistan for mild weather in spring and autumn. Ceiling fans are available almost in all rooms and work well in combination with evaporative coolers, as the latter directs the cooled air in one direction only while the fan 'homogenizes' it throughout the room.

In the 1970s, a new evaporative cooling technology was developed, that of using evaporating water to cool the air and then forcing this cooled air into the area to be cooled using a fan; this technology is also known as a swamp cooler. To date, this technology has been used successfully in Kurdistan because the climate is hot and dry, and this cooler adds droplets of water to the cooled area that both cool and increase the humidity at the same time. The equipment itself is quite large, but houses in Kurdistan generally have enough space for more than one cooler, especially on the roof. Hence, it could be housed directly in the required rooms, as shown in Figure *3-9*A, or the house or building roofs, and then distribute cooled, humidified air via ducts to the required rooms, as shown in Figure *3-9*B.

Figure 3-9: Possible positions of evaporative coolers in houses

The latest popular cooling technology that has begun to see widespread use over the last decade is the split air conditioning system. This technology is a very active cooler and can cool to very low temperatures, which enables it to control the hot extremes that occur in summer due to global warming. The main disadvantage of the split air conditioner is its large power consumption, which should not be underestimated as a factor, especially in Kurdistan due to the power shortages it frequently suffers.

3.6 Case Study – Erbil

Erbil is the most developed and, economically, the prosperous city in Iraq. This is due to some reasons, but the main reason it is the capital of the strategically and politically important region of Kurdistan, where all the Kurdish government's headquarters, and most of the international organizations, consulates, and companies, are based. Additionally, the frequent political conflicts in the rest of Iraq have made Kurdistan, and particularly Erbil, the safest region to live in and for job opportunities in the whole of Iraq. The International Organization for Migration's (IOM) report of March 2008 assumed that 2.7 million people had been displaced within Iraq during the previous decade, most of whom moved to Kurdistan [160] and, indeed, a majority of whom quite naturally relocated to Erbil as the largest city in Kurdistan.

Over the past two decades, Erbil has witnessed major investments in the building sector due to: i) its rapid growth; ii) the displacement of Iraqis from other cities and regions as previously mentioned; iii) Kurdistan was already in need of additional residential units, and iv) the rapid growth in commercial activities. As a result, a large number of residential projects have been undertaken in Erbil to cover the shortage in the residential sector. These units were and are still, being built without any proper code or strategy to decrease domestic energy consumption. This adds unnecessarily to the energy crises because of the new buildings are being occupied on a daily basis, increasing energy demand further.

Erbil is the largest city in Kurdistan and has the largest population of any city in the region; the summer is very harsh and dry as there are no rivers or lakes in the city, and it is generally much warmer than other cities in Kurdistan, so cooling demand is very high. Thus, Erbil was chosen as a case study to investigate the aim of achieving the greatest savings in energy consumption from cooling residential buildings by changing building fabrication and replacing conventional cooling systems (i.e., the split air conditioner) with a more novel form of cooling (i.e., the dew point air conditioner).

3.6.1 Case Study 1 (Ashti City 2) [161]

The case study building was selected from an investment project called Ashti city 2 in Erbil, as shown in Figure *3-10*. The project consists of 4000 one-storey and two-storey units. The one-storey unit was chosen because it is particularly desirable as such units are low-priced villas. This is typical of a design common to most of the other project units that are shown in appendix A.

Figure 3-10: Ashti city project [162]

The house is built on a 204 m^2 plot of land with a total building plan of 158 m^2 constituting a ground floor plan of 135.8 m^2 and with a penthouse of 22.6 m^2 on the first floor, as shown in Figure 3-11. The building plan consists of a kitchen, living area, two bedrooms, reception, storeroom, bathroom, and a penthouse. The building was constructed under the auspices of the interim Iraqi construction code, as shown in Table 3-4.

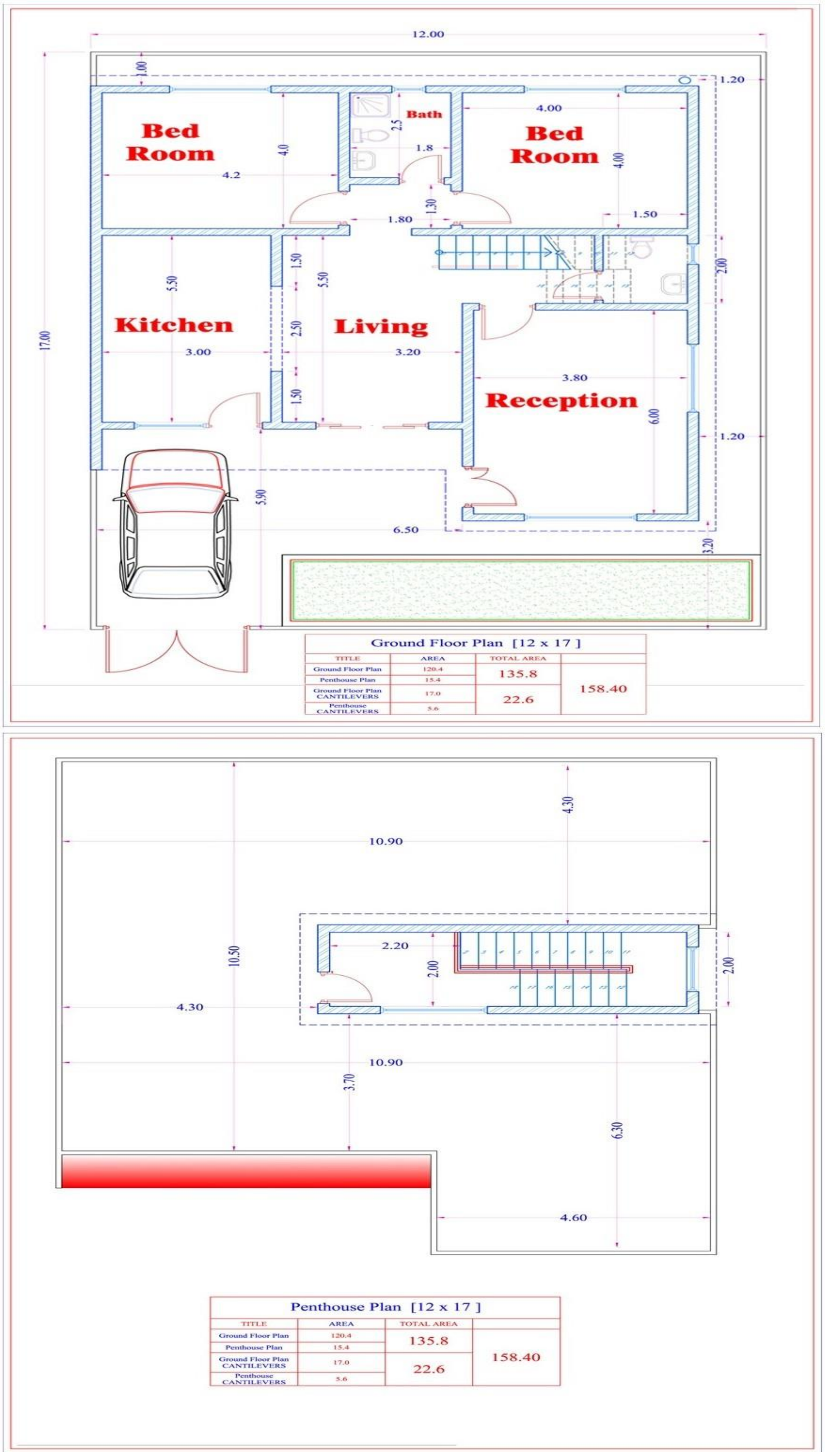


Figure 3-11: Map of the case study 1 building [162]

3.6.2 Case Study 2 (Heja City)[163]

This case study is a low rise multi-residential flat building from the Heja city project on which work commenced at the beginning of 2012 and is one of eleven units as shown in Figure 3-12. Although an apartment is not generally considered very desirable in Kurdistan, citizens are becoming more familiar and accepting of the concept due to the sharp rise in land prices, and the different cultures that have come to Kurdistan over the last few decades. Accordingly, apartment investment projects have recently come into widespread development across the whole of Kurdistan. Accordingly, such a unit has been nominated as our second case study.

Figure 3-12: Heja city project[163]

The building consists of four storeys, where each storey is comprised of four similar flats. The penthouse at the top of the building is used as a service area and storage for the residents. Each flat made up of two bedrooms, a living room, kitchen, hall, bathroom, and a storeroom, as shown in Figure 3-13. This kind of apartment building was constructed under the interim Iraqi construction code, as shown in Table 3-4.

Figure 3-13: Floor plan for the case study 2 building [163].

This case study building is one of the investment projects in Kurdistan. Affordability was considered when the proposal for such units was prepared by the government to allow the middle class and younger people to own their property. Figure 3-14 shows the construction stages required to build such apartments. This case study building is similar to many other flat buildings, that are built and sold to low /medium-income families in terms of design, the height of the building and numbers of floors.

Figure 3-14: Construction stages required for case study 2 apartments [self-reference]

3.7 Chapter Summary

A critical review was carried out about the area, concentrating on the current status. The chapter identified the associated difficulties and problems in terms of availability of power and water for such buildings.

Erbil is both the capital and largest city in the Kurdistan region of Iraq, where the climate is hot and dry in summer, as largely affected by climate change, and sees frequent hot extremes, and where the mean temperature is increasing. The Euphrates and Tigris are the two main rivers in Iraq, but neither of these rivers or indeed their tributaries runs through Erbil, so it is accordingly a very dry city. Erbil has developed rapidly over the last few decades, as it is the stronger economically overall in Iraq, and it is also of particular political importance.

Because the population of the city is growing – due to the importance of the city and, in particular, due to the immigration to the city as a result of the conflict and the instability in the surrounding areas , the city's energy demand is increasing significantly. A very high portion of domestic power consumption goes to air-conditioning in summer. The commonly used split-air conditioner system is very effective, but it consumes a lot of electricity. The split system could be replaced with an indirect evaporative cooling system, namely the dew point air-conditioner, that consumes much less electricity and a reasonable amount of water, such that it would be entirely possible to obtain acceptable power and water consumption in Erbil; indeed, a very similar conventional direct evaporative cooler is used successfully across the entirety of Iraq, including Erbil.

Due to the population boom in Kurdistan, especially in Erbil, the government facilitated and supported investment in residential projects. The case studies are two typical examples of residential buildings. The one-storey unit was chosen as the first case study because it is generally considered more desirable, as it is a villa and is of a relatively low price at the same time. It is one of 4000 such units in the Ashti city residential project. The second case study is a low-rise apartment from Heja city project that consists of eleven units; each unit comprises of four storeys with four apartments on each storey.

The chosen case studies in this chapter will be the basis of the modelling and prediction of the cooling load likely to be demanded by the air conditioning for each building. The optimum building fabrication required to minimize the cooling load will be described in a subsequent chapter.

Chapter 4: Cooling load of selected residential buildings

4.1 Chapter Introduction:

This chapter includes a detailed investigation into calculating the cooling load of both case studies employing two pieces of software (DesignBuilder and EnergyPlus). The objectives of the chapter are:

1- Modelling the floor plan of the baseline building in each of the case studies, where the buildings' details will be extracted from the information published for the projects and by making some reasonable assumptions about unavailable parameters such as window dimensions, locations, and glazing type.

2- Extracting the weather data from Erbil for use in the dynamic simulation, subsequently calculating the cooling load of the baseline models.

3- Identifying the most influential and optimum parameters for the baseline models.

4- Retrofitting the baseline models to determine the optimum parameters that guarantee the lowest cooling load and highest annual energy savings.

The process of modelling the baseline and applied parameters to the buildings is illustrated in Figure 4-1:

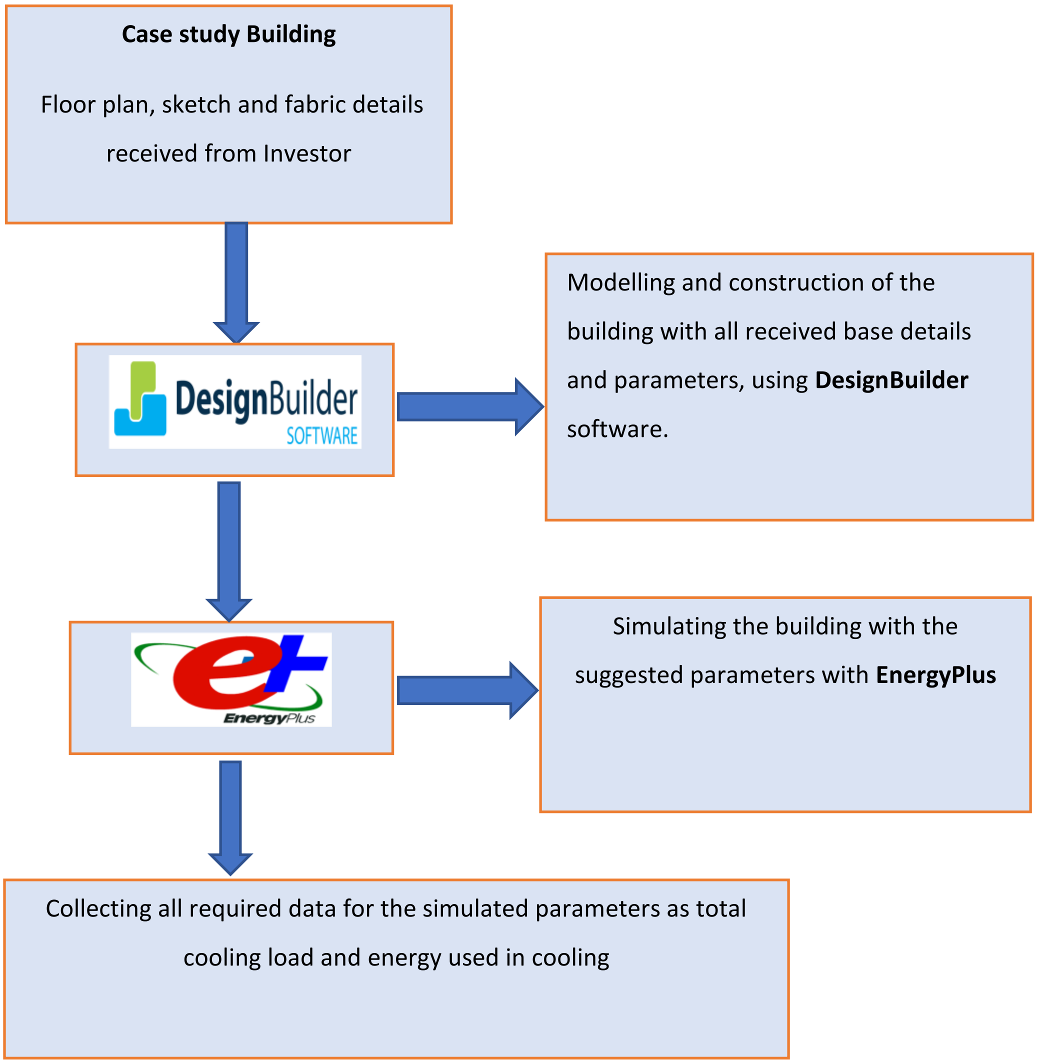


Figure 4-1: Overall house simulation layout

4.2 Case Study 1 - Ashti City House

4.2.1 Building Details and Construction Materials

The Ashti city house building is the first case study in this research, which was selected from among 4000 units with similar designs and construction in Erbil. The house floor plan obtained from the contractor is shown in

Figure 4-2. The building is built on a plot of 204 m^2, and consists of two large bedrooms of 16.8 and 16 m^2, a large living room of 26.8 m^2, a large kitchen of 18 m^2, a large reception room of 24 m^2, a bathroom of 5.7 m^2, a penthouse of 15 m^2 and a store of 3.8 m^2.

The types of materials and the construction assembly were chosen according to the old Iraqi interim building code that is still currently followed in Iraq, and which is illustrated in chapter 2. The building does not follow the proper construction codes as the government does not guide or force contractors to declare the details of their work. Information about the materials used in the house building, as received from the contractor, are briefly described in Table 4-1. Unlike developed countries building code, some materials or construction assembly were not disclosed in the Ashti construction reports, where the undisclosed materials and dimensions were chosen depending on personal references, knowledge, the practice followed, best assumptions, similar applications in the region and the availability of materials at the local market. Examples of these assumptions can be seen in the internal door materials and thicknesses, and the window frames and glazing type.

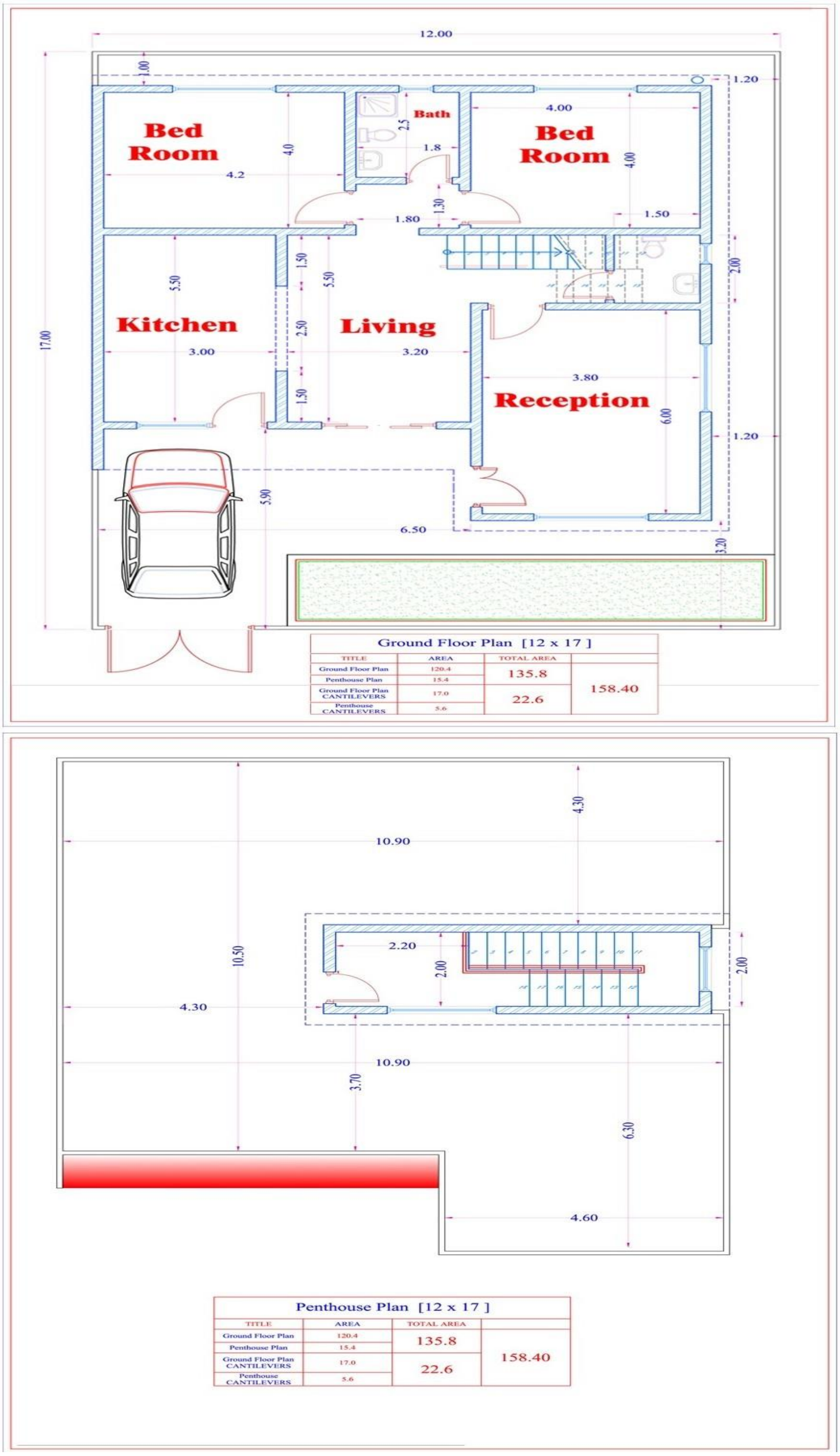


Figure 4-2:Ashti house floor plan [162]

Table 4-1: Ashti house construction details according to Iraqi construction code [22]

House module	Construction details
External wall	2 cm Cement & sand render + 20 cm hollow concrete block + 2 cm Gypsum
Internal partitions	2 cm Gypsum + 20 cm hollow concrete block + 2 cm Gypsum
Roof	20 cm reinforced concrete with 1% steel bars + 2 cm Gypsum
Ground floor	Soil + 10 cm gravel + 10 concrete + 2.5 cm Terrazzo Tile.
Internal floor	2.5 cm Terrazzo tile + 5 cm sand & cement mix + 20 cm reinforced concrete with 1% steel bars + 2 cm Gypsum
Windows	PVC (polyvinyl chloride) with one single pane of 6 mm
Façade or direction	Not considered
Door	Not specified

The construction materials for the Ashti house in Table 4-1are detailed in Table *4-2* Concrete blocks are the most frequently used materials in Iraqi buildings. Design builder software was used to module the house unit as shown in Figure 4-3. A cross-section of each part of the building is shown in Figure 4-4: A cross-section of each assembly in the house building

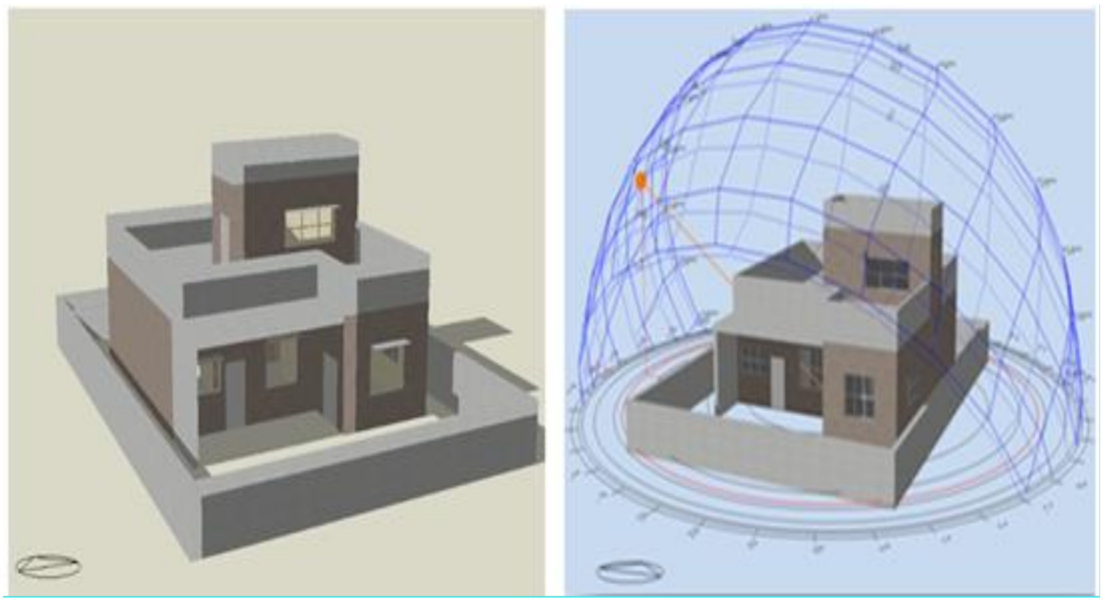


Figure 4-3: Ashti city unit modelled by DesignBuilder

Table 4-2: Material details input in modelling and conductivity

Material Name	Earth soil	Cast concrete	Concrete block Hollow	Floor screed	Floor tiles	Concrete reinforced steel 1%	External rendering	Gypsum plastering	Plywood	Roof screed
Thickness (cm)	25	30	20	10	2.5	20	2	2	0.3	6
Conductivity (W/m.K)	1.28	0.41	1.35	0.41	2	2.3	1	0.4	0.13	0.41
Density (kg/m^3)	146	1200	1220	1200	2243	2300	1800	1000	900	1200

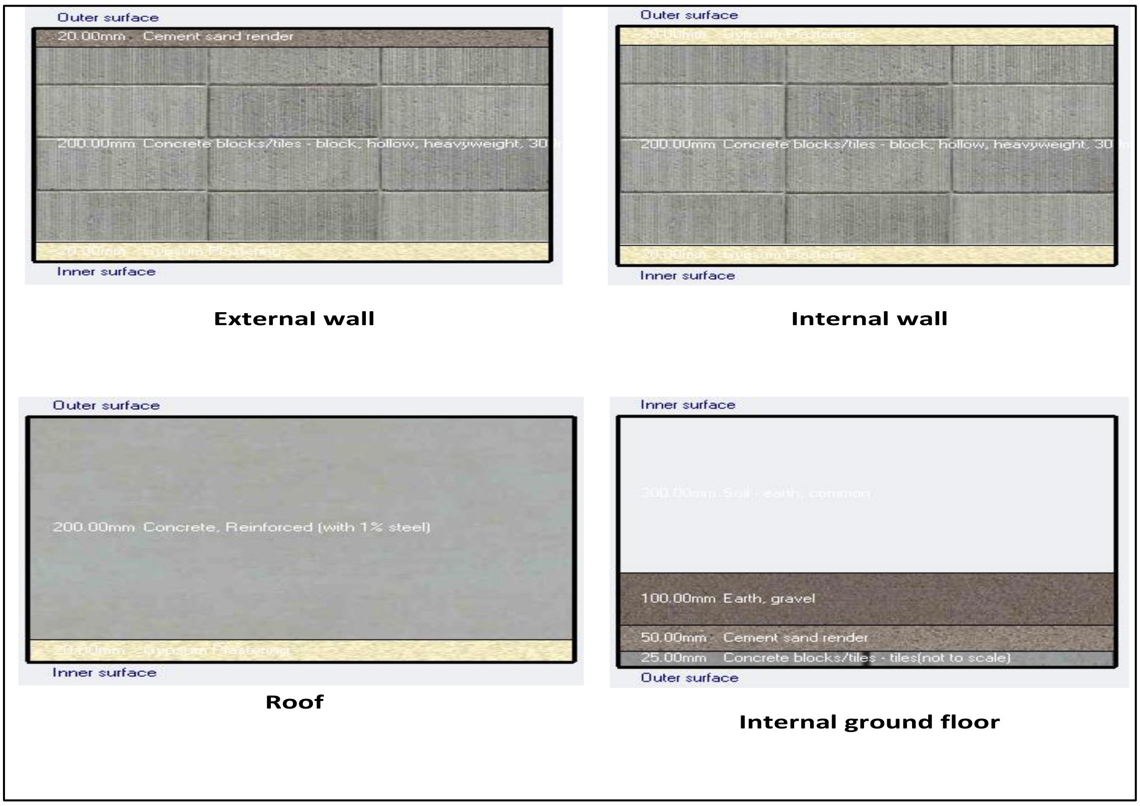


Figure 4-4: A cross-section of each assembly in the house building

4.2.2 Internal Parameter Activities and Schedules

All cooling demands simulated were designed to be realistic estimates of energy required for cooling and as such were calculated based on realistic occupancy schedules meaning that different internal gains and desired set points were dynamic through time. This differs from models simulating the cooling required to maintain a constant set point at all times but presents a more realistic view of cooling load. Once the building modelling and fabrication were complete, the building was set with various other important internal parameters per zone. The Ashti house consists of eight separate thermal zones, where the inputs all represented the internal heat gains. The parameters, namely lighting, occupancy, residential occupant's activities and equipment used in each zone were set separately to represent a typical family activity and to be as close as possible to reality. Some assumptions such as the operation times of lighting and internal equipment were made based on the authors existing knowledge about traditional Kurdish family's daily activities and practices. However, the cooling supply and operating times in the building zones were obtained via direct contact and over phone enquiries with the homeowner of the Ashti city unit. The occupier was asked in detail about the times that each zone is occupied and the cooling is turned on/off. The scheduling details are shown in Table 4-4.

This house was designed to accommodate five to six people, though this number could be up to eight people for some Kurdish families. Therefore, five to six people are considered a medium-sized family according to traditional family categories in Iraq. The number of occupants for modelling was assumed to be six people, that is, two adults and four children. More information about the occupants and equipment was added for the purposes of the simulation and are reported in Table 4-3. The final column of the table is the set temperature of 25°C that is within the comfort level of operative temperatures set by the ASHRAE for summer [59]. The type of lighting and its installation method will influence the modelling results; here, the popular white tube fluorescent light was used. The power lighting intensity in each zone was divided by the floor area for the sake of the simulation as some other zones sharing the same lighting energy with different schedules. There is a different ratio from one zone to another which is also dependent on the number of light units installed in each zone.

Appliances are significant sources of heat in some zones such as the kitchen, where the cooker is located. Each zone included some equipment that all families typically use such as a TV, computers, washing machine, fridge, cooker, and kettle. The energy requirements of each unit used were considered according to the usage schedule, although some equipment such as a cooker has a high-power rate per floor area, but is not used for very long each day.

Table 4-3: Occupancy, lighting, equipment, and activity in each house zone's

Zone	No of occ. during occupancy	Lighting W/m^2	Equipment W/m^2	Zone cooling set temp ^{0}C
Bed1	3	6	4	25
Bed2	3	6	4	25
Living	4	6	15	25
Kitchen	2	6	50	25
Penthouse	1	6	0	25
Reception	5	6	10	25
Store & bathrooms	0 1	11 11	0 10	NA NA

Generally, in residential buildings the metabolic and activity rates attributable to each occupant are limited to between very light housework activities to reclining, resting or sleeping. In this case, the metabolic rate per person ranged between 72-126 W/person multiplied by a factor of 1.0 for males, 0.85 for females and 0.75 for a child [45]. Table 4-4 shows the usage time and cooling, lighting and equipment patterns and the activities or the metabolic type per person as specified in DesignBuilder.

Table 4-4: House zones internal parameters times and schedules

Zones	Cooling supply schedule	Lighting schedule	Occupancy schedules	Equipment schedules	Metabolic
Bed1	22:00-9:00	12:00-15:00 & 19:00 - 23:00	23:00 - 9:00	22:00- 00:00	Resting/sleeping
Bed2	22:00-9:00	12:00-15:00 & 19:00 - 23:00	23:00 -9:00	22:00- 00:00	Resting/sleeping
Living	12:00-23:00	12:00-23:00	12:00-17:00 (half-Occ.) 17:00-23:00	13:00-17:00 19:00-23:00	Sitting-reclining
Kitchen	12:00-23:00	12:00-23:00	9:00-13:00 17:00-20:00	00:00 9:00 9:00-13:00 17:00-20:00	Cooking and eating/drinking
Penthouse 1st floor	12:00-23:00	12:00-23:00	18:00- 20:00	--	Walking about
Reception	18:00 -23:00	18:00-23:00	18:00 -21:00	18:00 23:00	Seated quietly
Store & bathrooms	Not cooled Not cooled	18:00-22:00 12:00 -22:00	9:00-12:00, 17:00 - 20:00	9:00-12:00	

Blinds or internal shadings are vital in Middle Eastern residential buildings; they are principally used to maintain the privacy of family members, and secondly for providing shade from the sun's radiation, so reducing the sun's heating effect. Setting a schedule for the blinds is very important in preventing the sun's radiation from entering the conditioned zone. Figure 4-5 shows the scheduling of the blind that was used in the EnergyPlus modelling software to provide and reduce the cooling load. The habit followed in the Kurdistan region is to have all the blinds closed while people are asleep and to open them to expose the rooms to sunshine during the mornings when temperatures are cooler. In the afternoons when it gets hot, people close the curtains or blinds down, though they are left partly open to allow some sunlight to enter, and are open more in the evenings. When the outside temperature exceeds 30°C then people generally close the blinds down, so weather plays a role as well.

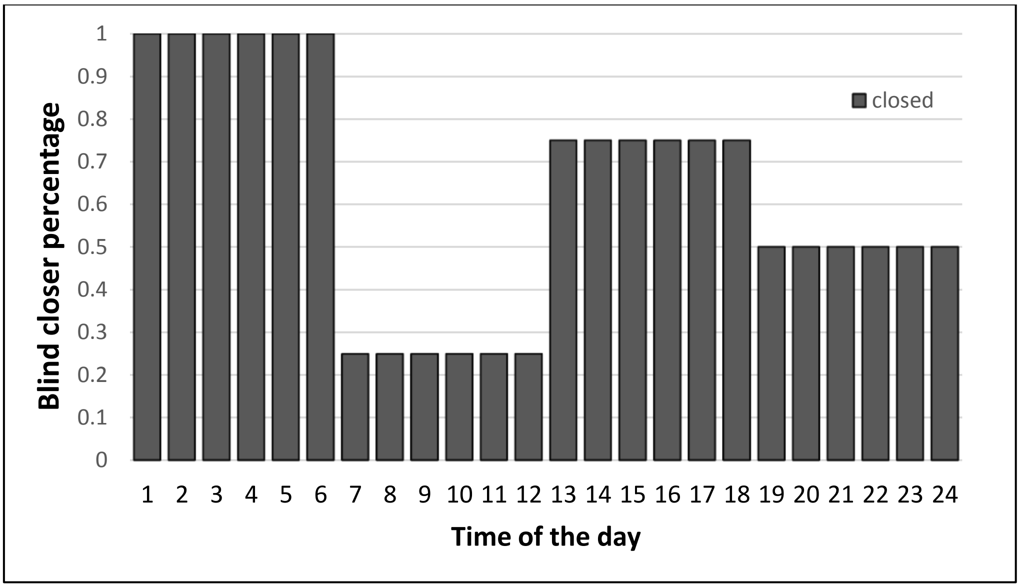


Figure 4-5: Internal shading, blind operating times each day

Clothing acts as personal insulation to provide comfort to the body and provide protection from the effects of the outside environment. Generally, in hotter climes, people wear fewer clothes that are typically made of thinner fabrics. In this modelling process, clothing is assumed to be 0.5 Clo for both males and females as shown in Figure 4-6 from April to September, and it is assumed that only family members are at home and that no extra clothing is worn. This has been verified with various family members through directly enquiring and personal references and phone calls about the type of clothing. However, the intention of this study is not to research the comfort level of occupants, but rather we assume the operative temperature of 25°C was comfortable. This temperature is accepted by people living in hot climates according to ASHRAE standard 55. The comfort zone of such a climate is 24-27°C, keeping in mind that the building is only residential and there is no hard or physically heavy work involved in the zones. For that reason, the metabolic rates are accordingly is between 70-120 W/person for the studied season.

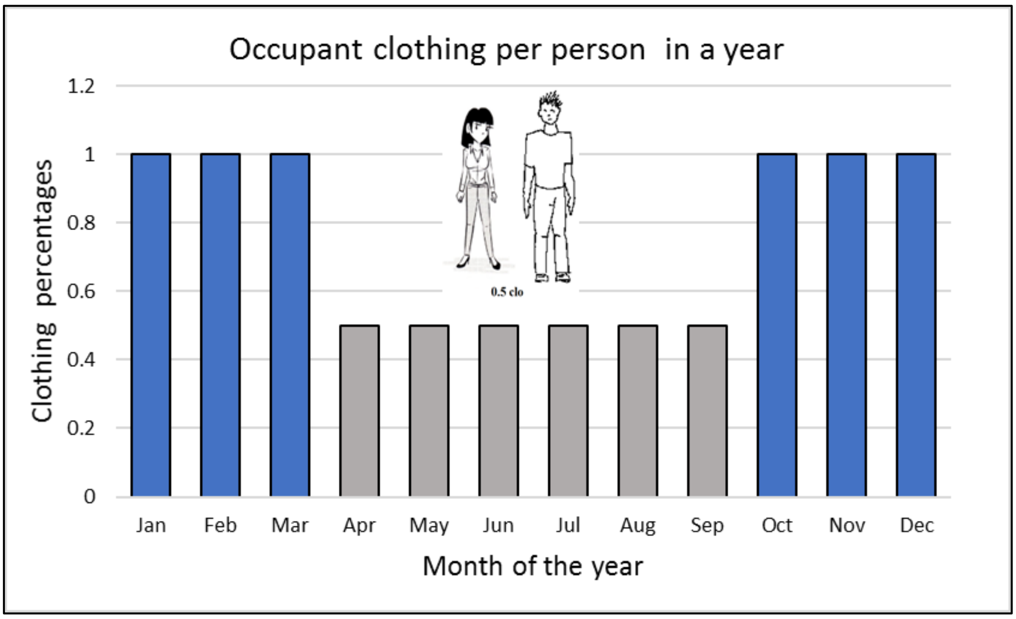


Figure 4-6: Clothing of occupant during the cooling season

4.2.3 Cooling Supply and Schedule

The cooling supply was set for each zone separately, as shown in the first column of Table 4-3: Occupancy, lighting, equipment, and activity in each house zone. Bedrooms are cooled at nights between 22:00-9:00 while in other zones the cooling supplies and systems are switched off. In the morning when it is cool, and hence not much cooling is required, all systems are switched off between 9:00-12:00 when some of the occupants are out, and cooling is not needed. The cooling is switched on again in the kitchen, living and the penthouse between 12:00-23:00; these are the main zones in the building as the kitchen and living room are the most frequently used rooms. The reception is mostly used for visitors though family members sometimes use it between 18:00-23:00. The kitchen, penthouse, reception and living room are cooled together daily between 18:00-22:00, and at the peak time between 22:00-23:00, all zones in the house are cooled at the same time.

Each zone in the building is a separate thermal zone and has its own cooling load and energy profile. The calculation of the cooling load for each zone included the effects of the external conditions due to solar heat gain through the building shell. It also includes the internal heat gain from people, lights, and equipment. The load also represents the demand due to the cooling system to bring the internal temperature down to the desired set temperature of 25°C. Each zone has its own peak time according to the cooling schedule that was set in each given zone. The peak load for one zone is not necessarily representative of the peak for another, as peak usage depends on various factors such as orientation, cooling schedule, and other forms of use.

4.2.4 Cooling Load

Cooling load is the most important part of the study; the aim is that this should be minimized. The total cooling load of any thermal zone comprises two main sources, namely the external and internal heat gains, as shown in Figure 4-7. The external heat gain covers the building fabrication with its associated transfer due to the effect of external weather conditions such as temperature, solar irradiation and wind. The internal gains are due to such factors like occupancy, lighting, usage pattern, activities, type of zone, metabolism of occupants and the equipment used in the zone that produces heat and increases the internal temperature, which subsequently raises the cooling load.

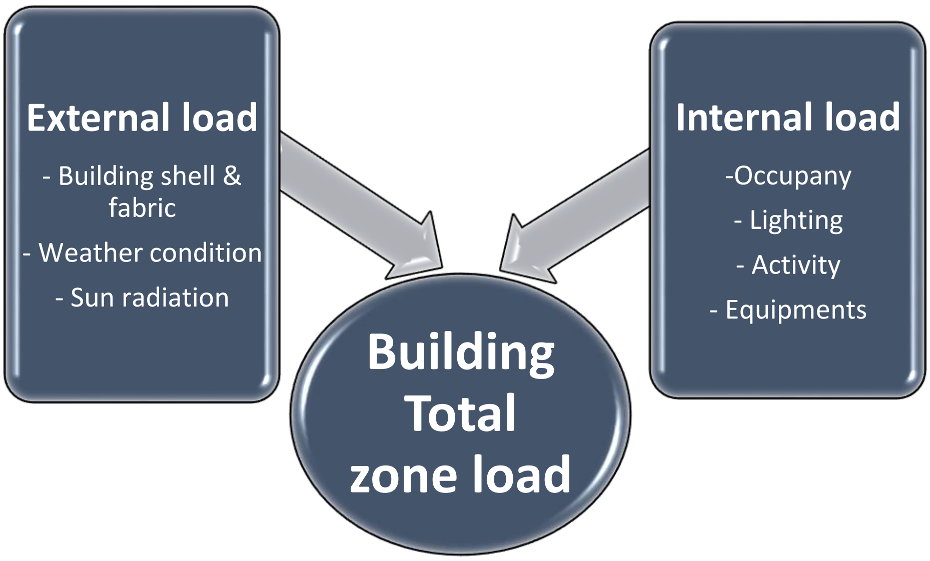


Figure 4-7: Total load parameters and calculation method

The house module was transferred from DesignBuilder to the EnergyPlus software for the purposes of performing a dynamic energy simulation, where the latter software was chosen to save time as it is fast, easy to control, and easy to apply the different parameters involved. The house module consisted of six different thermal zones with different cooling schedules; after calculating the cooling loads separately, these were all been summed to represent a single, overall profile, resulting in an effective single cooling load that represents the final load pattern according to the schedules inputs supplied.

When a building is not cooled to extract the gained heat from the walls, roof, glazing, and internal activities. Internal temperature rises as shown in Figure 4-8. This profile is the average internal temperature in all zones of Ashti house when no cooling systems are operated. During the nights when the ambient temperature is dropped, the internal temperature is still high due to building shell effects and indoor activities. The temperature fluctuates over time, but it is not less than 35 ^{0}C and in some zones like the kitchen is rising to 44 ^{0}C because of the appliances used.

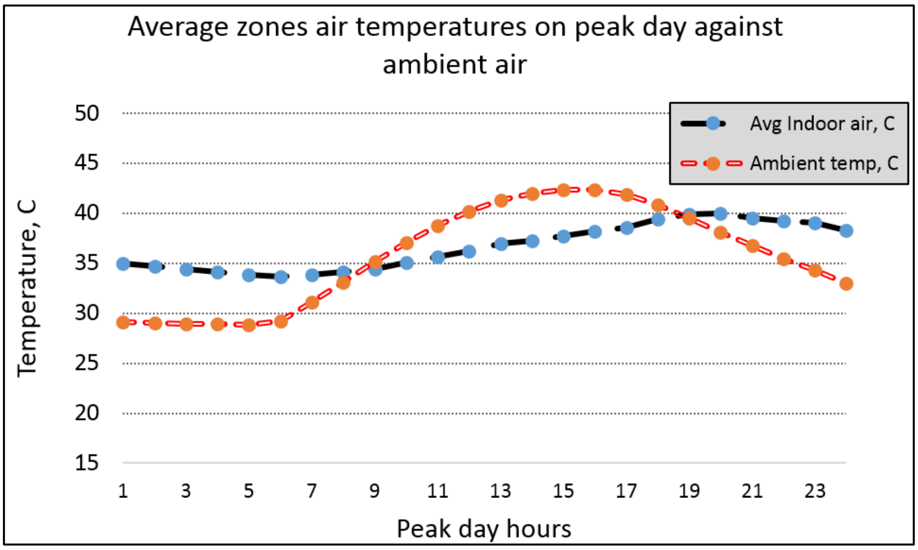


Figure 4-8: Peak day average zones internal and the ambient temperature ^{0}C.

Figure 4-9 illustrates the scheduled hourly-simulated cooling load for the house over a single day. Specifically, it represents the 21st July, the hottest day of that year. This cooling profile pattern was obtained according to the cooling supply schedule shown in Table 4-4 with the internal temperature fixed at 25°C. The air conditioning in Bedroom one and bedroom two was operated at the same time, allowing a cooling load of 3.47 kW to be determined, which was gradually reduced because of decreasing internal heat gains and the effects of the external conditions, such as temperature and solar irradiation. The cooling is switched off at 9:00, which then sets back to zero from 9:00 to 13:00 when the cooling is switched off. Cooling is required after 13:00 in several zones such as the kitchen, living room and the penthouse. Therefore, the load starts to increase, reaching 10.58 kW, which is high in the morning because of accumulated heat from the mass or shell of the building – as per this load pattern is for 21st July – and because of internal heat gain. The load declines sharply to 6.92 kW, then becomes stable and gradually increases from 6.9 to 9.39 kW until 18:00. This increase is the effect of the temperature of the building shell causing heat gains within the building in the late afternoon. After 18:00, the load jumps to 15.17 kW because the reception zone adds to the total load and the accumulated heat. Then, the load decreases slowly, reaching 11.45 kW at about 22:00. The peak time is 23:00 when the load reaches its highest of 17.47 kW because, at this time, the cooling is on at the same time in all the house’s zones. The load drops sharply again to 5.27 kW at 24:00 because the cooling is only on in the bedrooms at sleeping time.

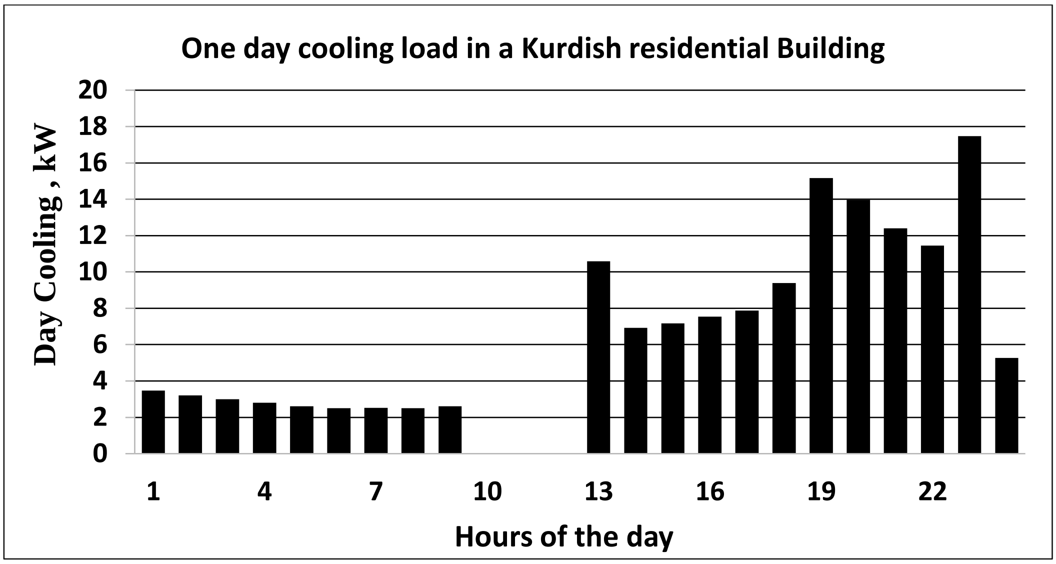


Figure 4-9: Ashti house base model, scheduled total load profile

Figure 4-10: House Total zones cooling compared to the scheduled timing and solar irradiation on the peak day shows the comparison of the cooling loads for the house in case if the house was cooled as scheduled and the same house cooled for all day regardless of the schedule (24 hr /On), with the same internal set temperature as 25^0C. It is noticed that the peak cooling load drops in case of the whole day cooled house, due to the absence of any uncooled zones effect. It also shows the influence of the sun irradiation on the building, as the peak radiation is at midday, but the peak cooling is about six hours later because in the afternoon the building radiates the heat out.

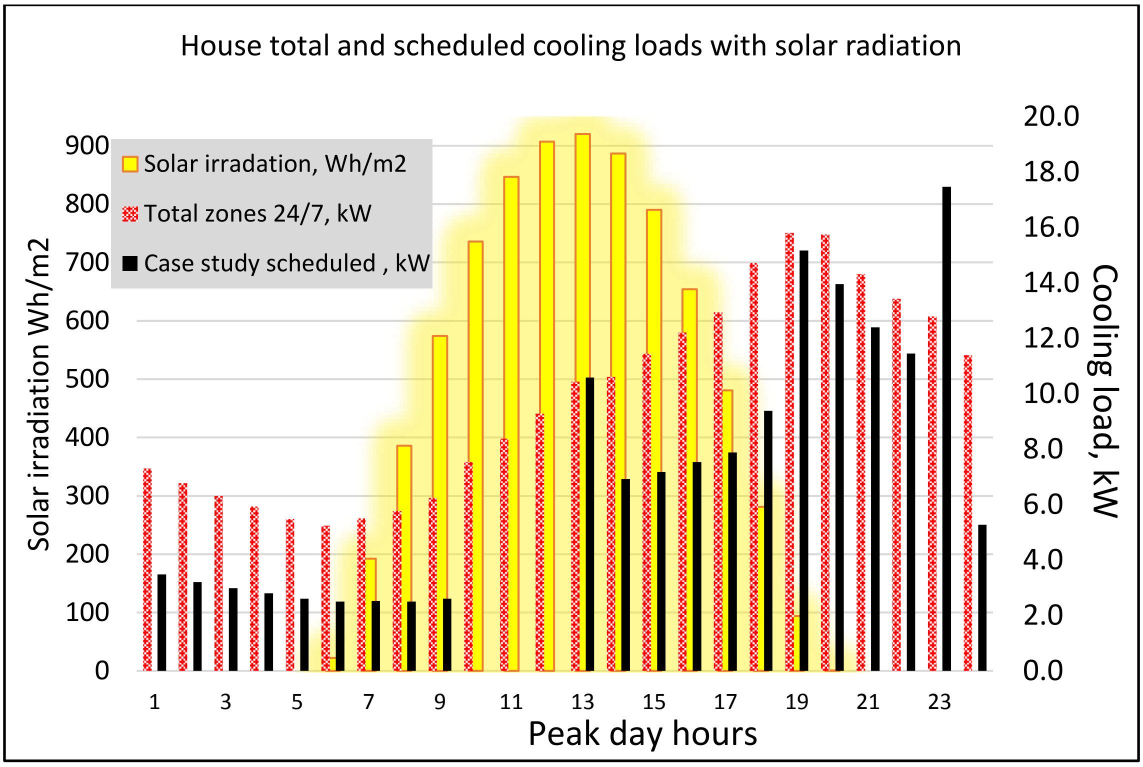


Figure 4-10: House Total zones cooling compared to the scheduled timing and solar irradiation on the peak day

4.2.4.1 Weekly Load Profile

The weekly cooling load of the baseline profile for the Ashti house understudy is illustrated in Figure 4-11. The load is a multi-replicate of Figure 4-9. The variation in the load is representative of the external weather conditions and effects of solar irradiation when keeping the internal parameters otherwise unchanged. The peak load in the hottest week of July was between 12-17.4 kW, giving an average load of 14.78 kW. Although the peak load for the hottest day was found to be 17.46 kW, this occurs only once a year and the 'typical' maximum value is closer to 14.7 kW. In this case, the peak is always at 22:00-23:00 when all zones need cooling.

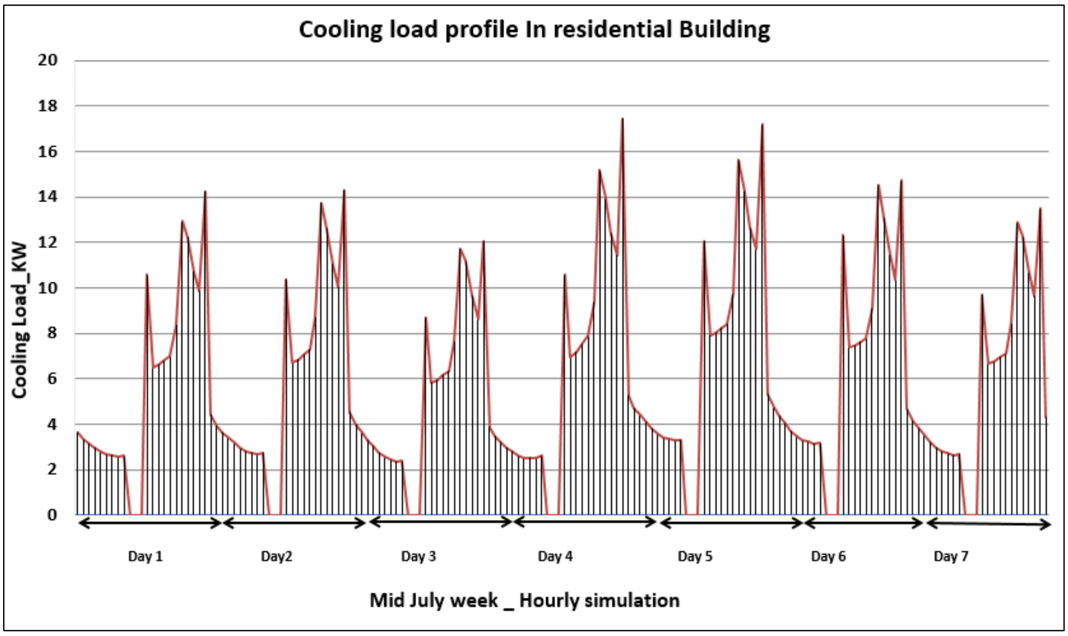


Figure 4-11: Scheduled Cooling load profile for the hottest week of July

Figure 4-12 shows for comparison the realistic scheduled cooling loads used against the cooling load if the house was maintained at a constant internal set point of 25^{o}C. It could be noted from the comparison of the two loads, that the peak load when scheduled is higher than when all the house cooled for all day, this is because of the accumulated heat in the zones when uncooled, which raises the internal temperatures and increases the cooling load.

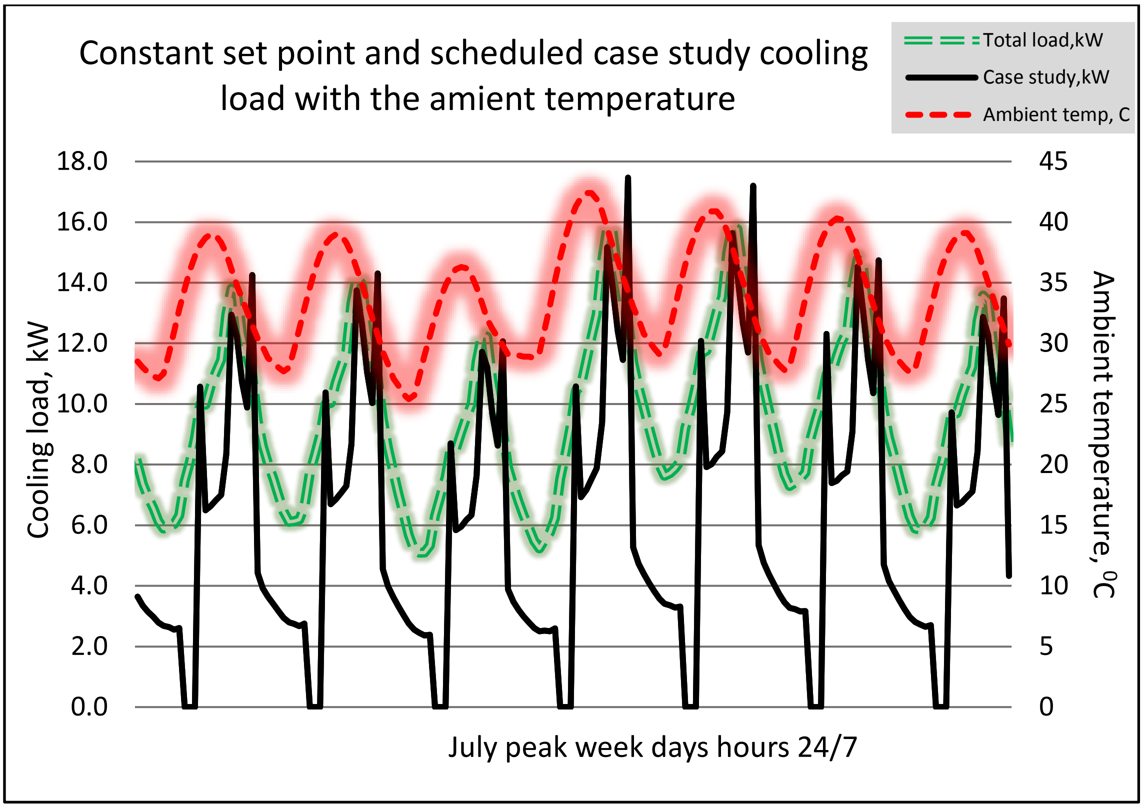


Figure 4-12: Weekly house, constant internal set point and scheduled load comparison with the external temperature

4.2.4.2 Monthly Cooling Profile

Figure 4-13 illustrates the hourly load profile of the house for July, which shows the simulation results for thirty-one replications of Figure 4-9. The pattern shows the effect of the climate on the cooling load, with the average of the peak loads which occurs at 23:00. The cooling load is calculated to be 12.73 kW, while the same average for the hottest week shown in the graph, as situated towards the end of July, is 14.78 kW. It may be noted that the peaks fluctuate between 9.9 kW and 17.4 kW. Figure 4-14 shows the consequent hourly simulated cooling load for the house, where the recurrent peaks are higher in the last ten days of July and August.

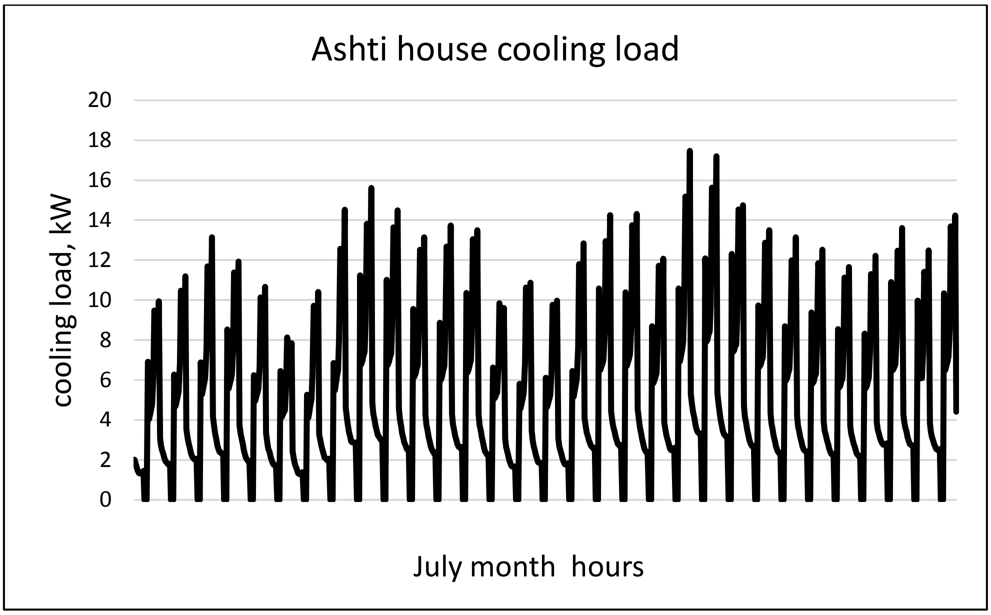


Figure 4-13: Hot July month load profile

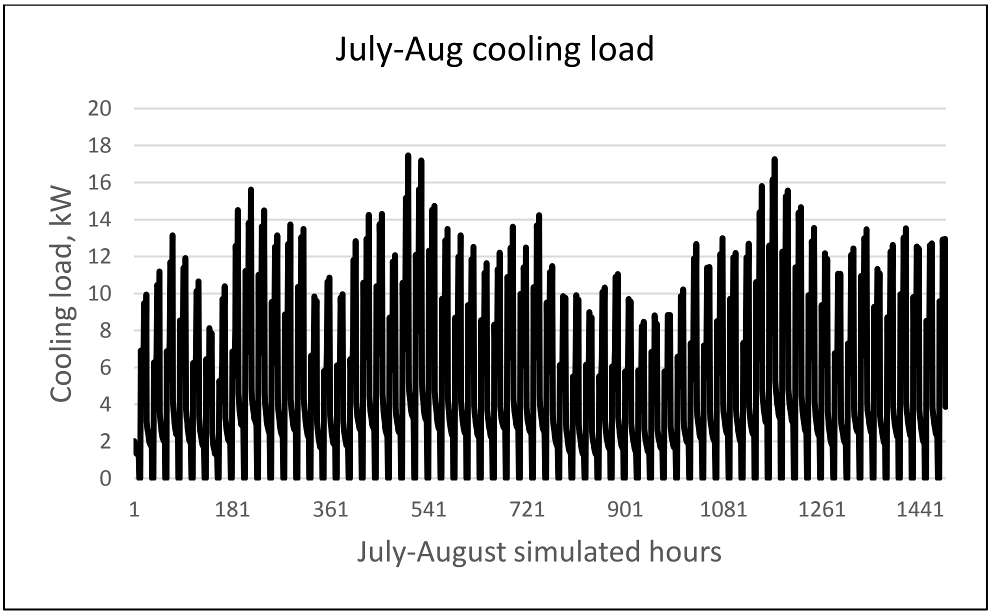


Figure 4-14: July-August hourly simulated cooling load profile of the house base case

4.2.5 The Primary Results of the Baseline Module

The primary results of the baseline module for the simulated season between April and October indicated that the greatest part of the energy consumed in the building is used by the cooling system (78%) in order to reach the desired set temperature of 25°C; other electrical equipment uses 15%, then the lighting consumes 7% of the total energy used 13,104 kWh for six months, this is shown in Figure 4-15. The greatest heat gain in the module was from the building fabric, the sun and the assembly of the building shell; consequently, 93% of the cooling load is due to active sensible cooling, while the remainder (7%) represents latent cooling.

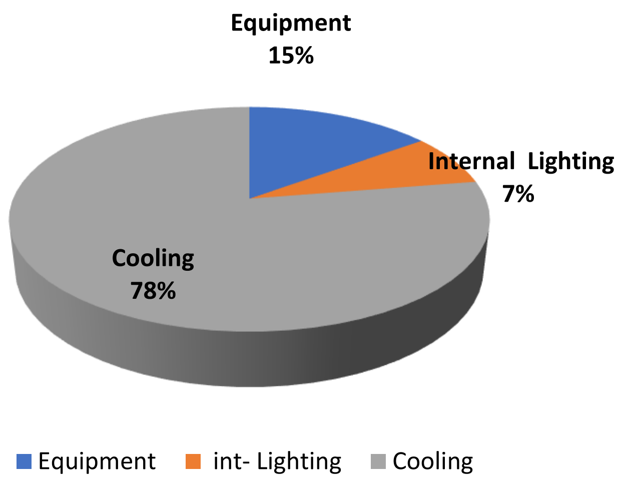


Figure 4-15: The annual energy consumption in the baseline module house

The greatest effect on the building cooling load is from the external walls' heat gain, which represents 35.13% of total heat gain, followed by the roof at 30.19%, internal walls at 12.5% and solar gain through the windows at 9.6%. The solar gain from the windows was expected to have a much larger effect, but due to the internal shading (blinds) which cover the windows, especially in hot and high solar irradiation days, the effect on the general cooling load of the building is minimized. All other parameters such as occupants, equipment and air infiltration have relatively little effect at around 6% each. Thus, the results show that the walls and roofs are the main factors affecting the cooling load. It is very clear that most of the energy is consumed is by cooling, as shown in Figure 4-15, is the result of the baseline model simulation and the combination of all the above heat gain percentages which illustrates the maximum share of cooling consumption.

The daily cooling load based on the hottest day in Kurdistan (21st July in the weather file) was simulated using a traditional air conditioner. The maximum cooling load per zone, per square metre, and total house average were predicted, as shown in Table 4-5. The penthouse requires the highest portion of the load (294 W/m$^{2.}$) as it is exposed to direct solar irradiation from all sides (walls and roof), and the average load for whole the building is 243 W/m^2, which includes 127 m^2 of conditioned spaces.

Table 4-5: Maximum cooling load for each zone per m^2 on 21st July.

	Bed 1	**Bed 2**	**Kitchen**	**Living**	**Reception**	**Penthouse**	**Total house Average, conditioned 127 m^2**
Zone max cooling load W/m^2	240	219	260	159	286	294	243
Total Zone max cooling load, W	3824	3482	3873	3565	6102	3714	4093

The overall combined hourly cooling load in the building (all zones) was simulated, where the peak cooling of 17.47 kW on was 21st July at 23:00-24:00, as illustrated in Figure 4-9.

4.2.6 Impact of the Different Parameters

The annual cooling energy (kWh), and the maximum cooling load (kW) for the baseline module was simulated by the EnergyPlus software, after which the simulation was repeated while changing one of the main parameters, as shown in Figure 4-16 and keeping the remaining parameters unchanged. This was to independently evaluate the influence of each parameter on the baseline module's load and energy. The baseline module parameters are cement block, no insulation, 6 mm single clear window with no suspended ceiling, and no overhangs, as shown in Table *4-2*. The maximum daily cooling load for the baseline module was 17.47 kW whilst the annual cooling energy was 13104 kWh, as reported in the first column in Figure 4-16.

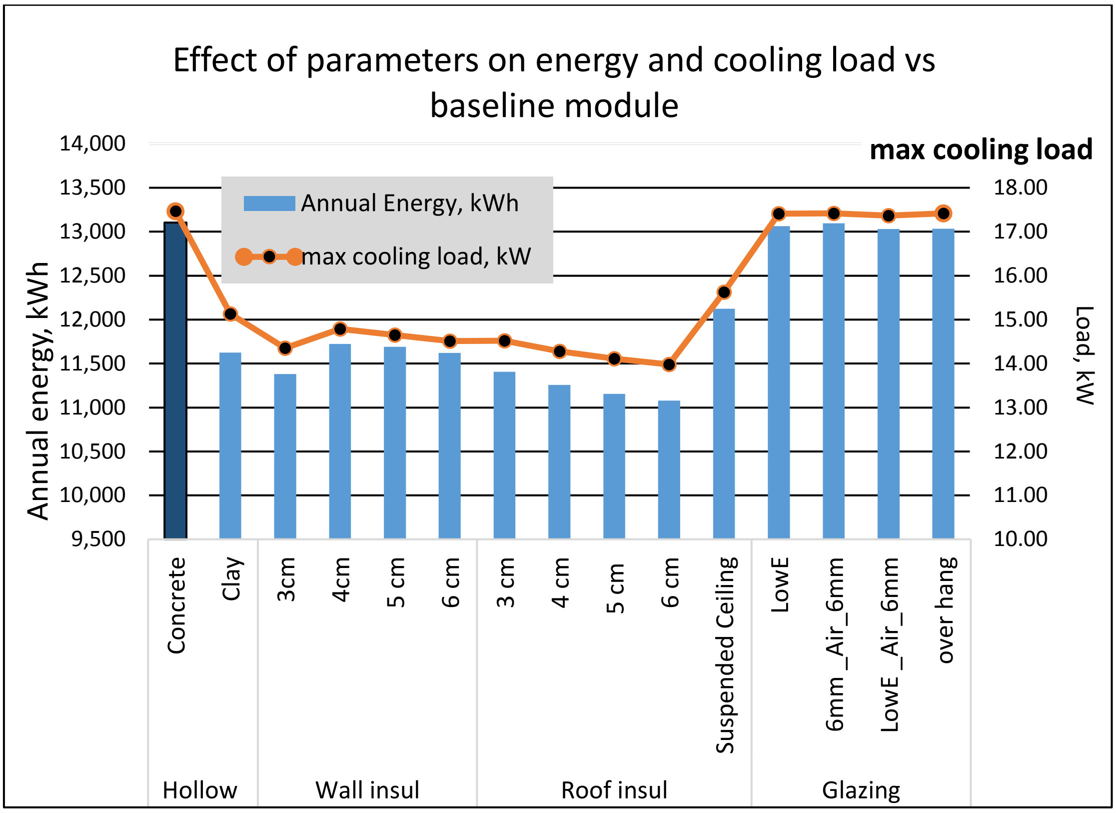


Figure 4-16: Effects of individual parameters on the peak cooling and energy consumption

The graph also shows the annual energy saving due to each parameter. The hollow clay brick, as in Figure 4-17, could minimize the maximum daily cooling load from 17.47 kW to 15.13 kW and annual cooling load from 13104 kWh to 11626 kWh when used to replace the hollow cement block of the baseline module, giving an annual saving in energy consumption of 11.3%.

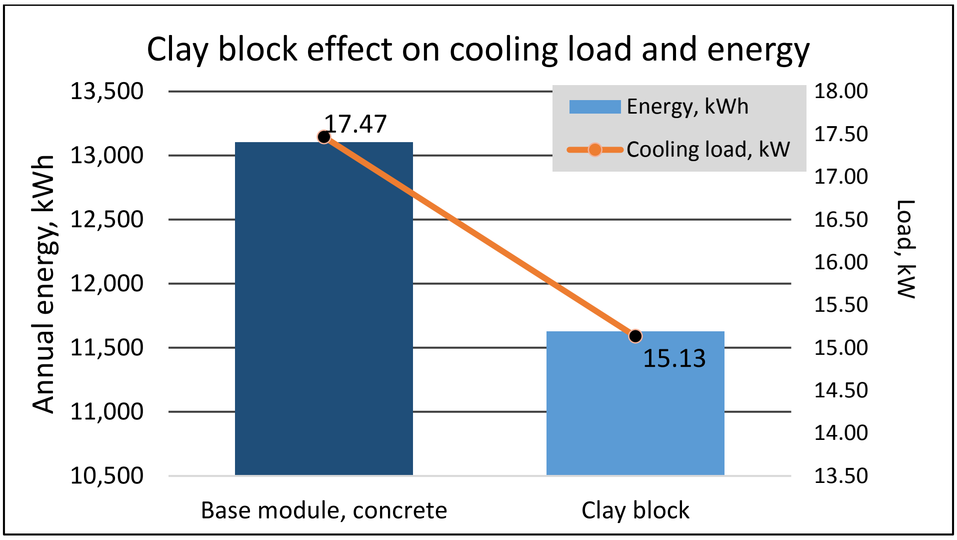


Figure 4-17: Effect of hollow clay blocks on cooling load and annual energy consumption

3 cm of insulation in the wall was found to be the optimum thickness, reducing the maximum daily cooling load from 17.47 kW to 14.35 kW and the annual cooling energy from 13104 kWh to 11382 kWh with an annual energy saving of 13.1%. Hence, there is no need to use thicker insulation as this would result in extra cost for a negligible effect. Increasing the thickness of the outer insulation from 3 cm to 6 cm would result in reducing the maximum cooling load from 14.35 to 14.51 kW, while the energy would increase from 11382 to 11620 kWh, as shown in Figure 4-18.

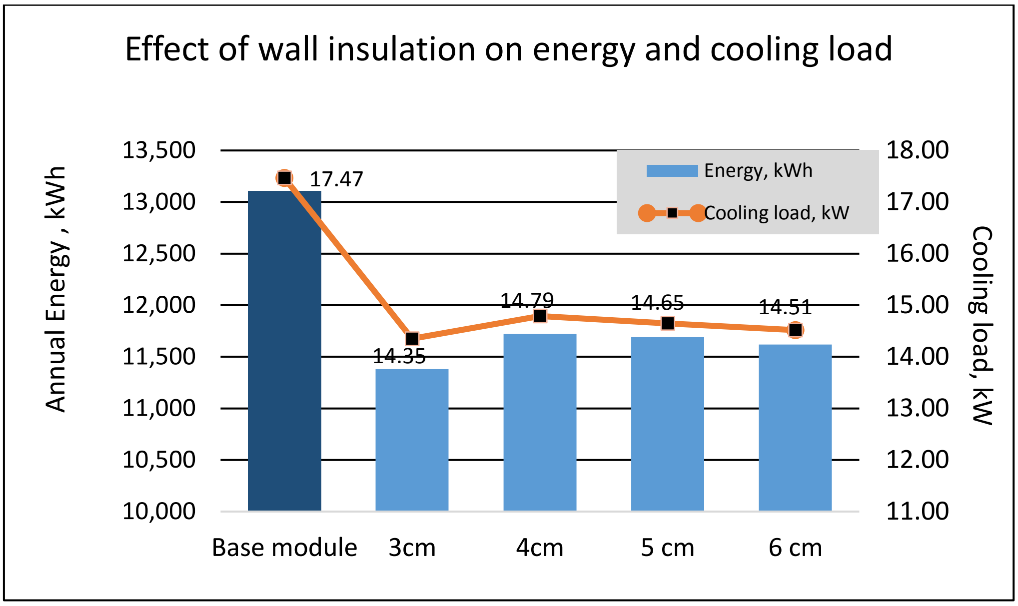


Figure 4-18: Effect of wall insulation on cooling load and annual energy consumption

Roofs are a major concern about increasing heat gains, especially if the construction materials are of high thermal capacity, such as the concrete roofs of Iraq. Figure 4-19 shows four levels of insulation from 3 to 6 cm and a suspended ceiling with a 30 cm air gap and a layer of gypsum board. The 3 cm thick insulation reduced the cooling load to 14.52 kW while the 6 cm reduced it to 13.98 kW, whilst the 4 and 5 cm thick insulation did not have a greater impact than the 3 cm thick. The annual energy usage with 3 cm insulation was 11407.3 kWh, whilst with 6 cm thick insulation usage was 11077.21 kWh; the difference of 330 kWh is negligible given that the thickness has been doubled. The impact of the suspended ceiling is also obvious, reducing the maximum daily cooling load from 17.47 kW to 15.63 kW with a reduction in the annual energy requirements for cooling from 13105 kWh to 12124 kWh, and an associated annual energy saving of 7.5%. A suspended ceiling is a very popular method of insulation and a traditional means of decorating the ceiling in Kurdistan as it provides cosmetics for the roof as well as insulating the roof from the internal zones. Although the effect of a suspended ceiling is not as great as that of the insulation it does not require additional coverage, which would otherwise mean additional costs improving the building. Generally, the effect of the ceiling insulating is due to the high thermal conductivity of the roof, because the building being tested is a one-storey building and is directly exposed to the hot sun.

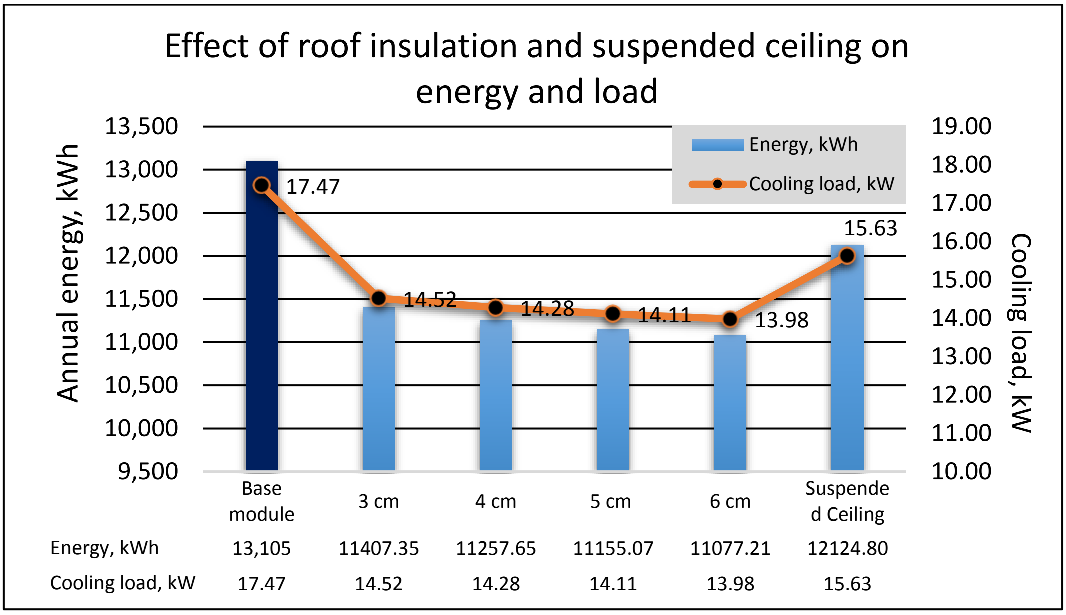


Figure 4-19: Effect of roof improvement on cooling load and annual energy consumption

The impact of double-glazed windows and low emissivity glazing is generally very low on cooling load and energy savings, as shown in Figure 4-20. Indeed, the annual energy saving is only between 0.1-0.6% this is because of the low window/wall surface area ratio and the availability of the internal shading. For the same reasons, the importance of the overhang is also negligible, showing only a 0.5% saving as it had only a 0.5 m projection without tilting angle over the window, as shown in the simulation results. Figure 4-21 shows the comparison effect of all applied parameters separately to assess their effect if any of the parameters were applied.

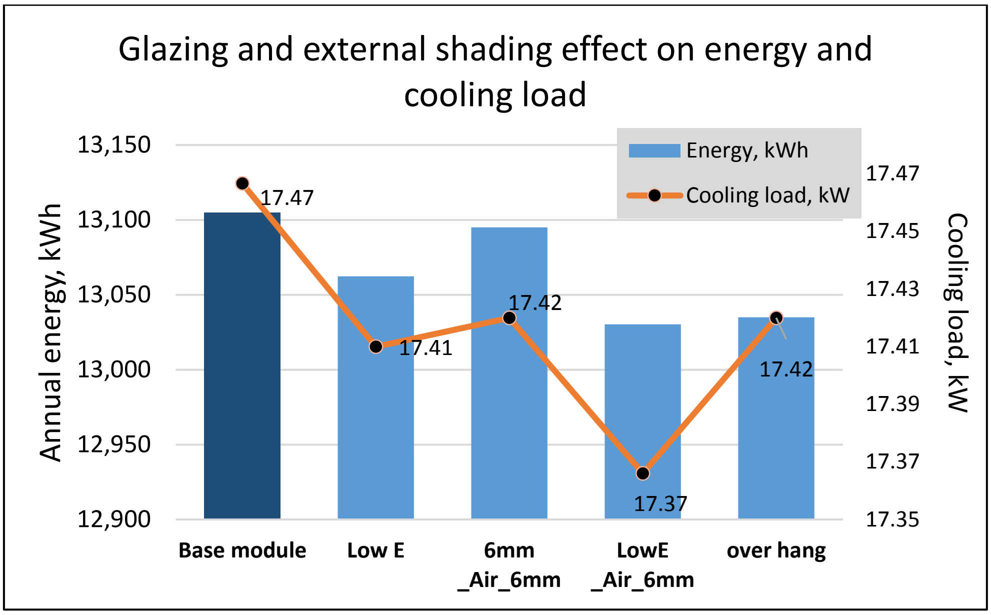


Figure 4-20: Effect of glazing and external shading on cooling load and energy usage

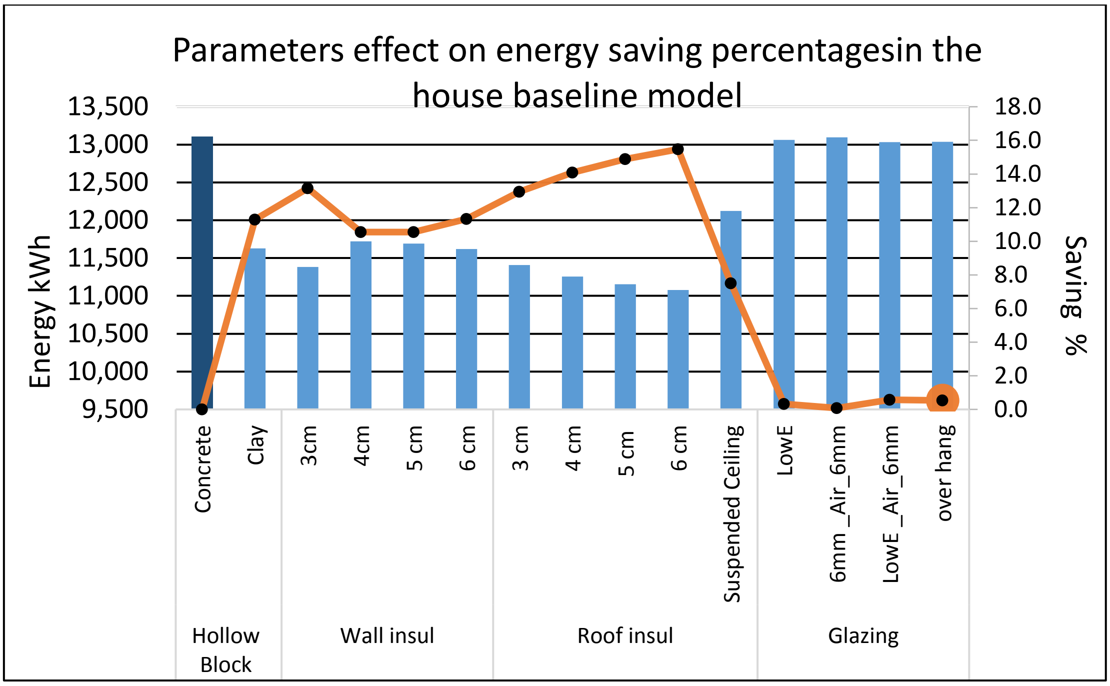


Figure 4-21: Percentage saving per parameter

4.2.6.1 Building Orientation Effect

The baseline module orientation faces South (0 degrees), but the building was simulated with other orientations of 90-West, 180-North, and 270-East to investigate their influence on the cooling load and energy consumption in the building. The results showed that the western orientation has a minimum deisgn day cooling load of 17.2 kW comparing to other orientations, but the annual energy consumption was at its maximum of over 13600 kWh. The minimum consumption was with the building orientated towards the North, with an energy use as low as 12949 kWh, as shown in Figure 4-22. Hence, the minimum cooling load does not necessarily correspond to the minimum energy consumption.

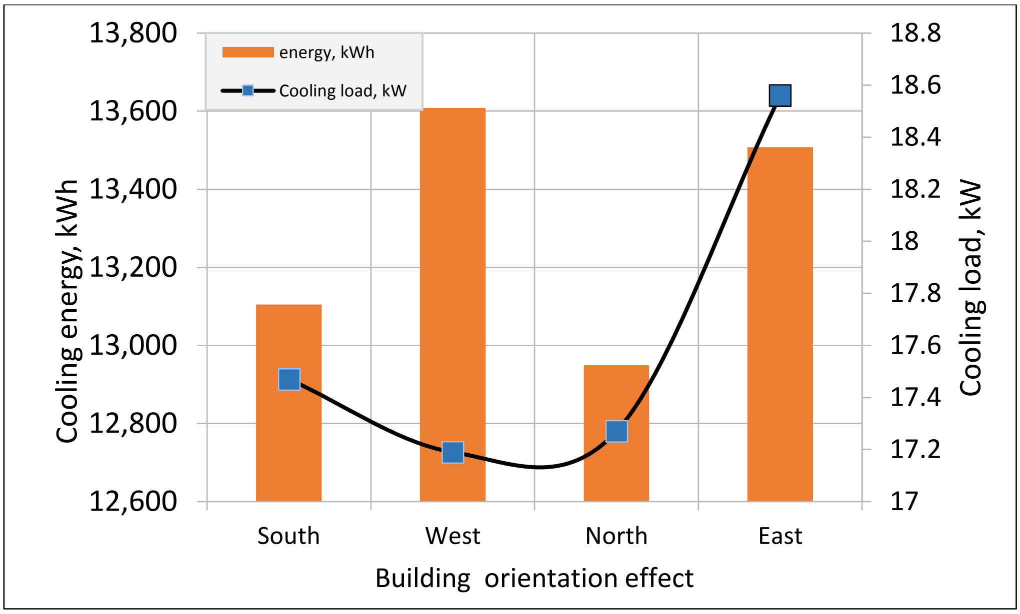


Figure 4-22: Effect of orientation on the load and energy usage on the baseline module

4.2.6.2 Multi-parameter Effect

Following the evaluation of each parameter individually in comparison to the baseline simulation's total energy and load, parameters were then combined. Further simulations were conducted to determine the change in cooling load, and energy consumption obtained when retrofitting the building with the combined parameters.

Figure 4-23 illustrates the parameter combinations resulting in a further 384 multi-simulations that were used to retrofit the building using different parameters.

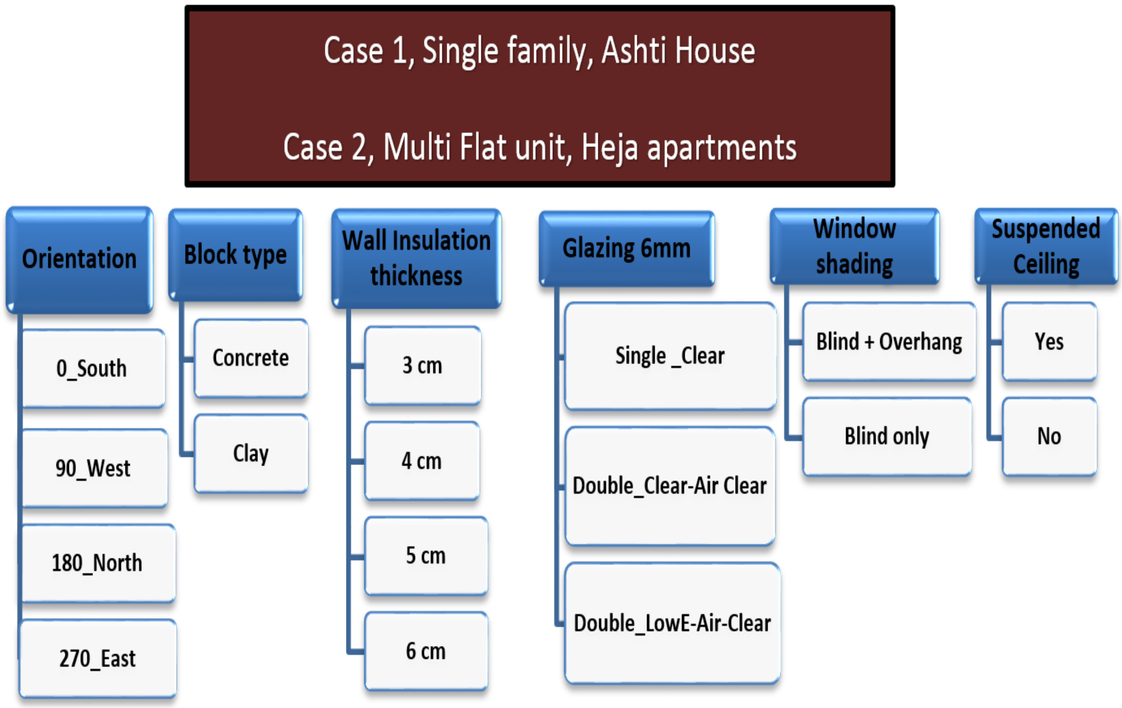


Figure 4-23: Schematic of the multi-simulation process

Each of the 384 parameter combinations was simulated for a year, and the results analysed to identify the optimum combination of parameters leading to the lowest energy consumption and cooling load. It was predicted that the parameters hollow clay brick, 6 cm insulation and suspended ceiling, low emissivity glazing and overhang with the Northern orientation of the building was given the maximum savings. It was shown that the peak load could be reduced from 17.47 kW to 9.92 kW, as shown in Figure 4-24, whereas if only the clay hollow blocks and 3 cm insulation with the suspended ceiling were added, the load would be reduced to 11.16 kW with an annual energy consumption of 10141 kWh. The difference is relatively small compared to the number of changes, such as adding low emissivity glazing, doubling the insulation thickness and adding additional external overhangs over the windows. This result is a strong indication that the optimum insulation thickness is 3 cm for the external walls, and that the window glazing being replaced with low emissivity glass and adding overhangs externally had no obvious effect on cooling load reduction.

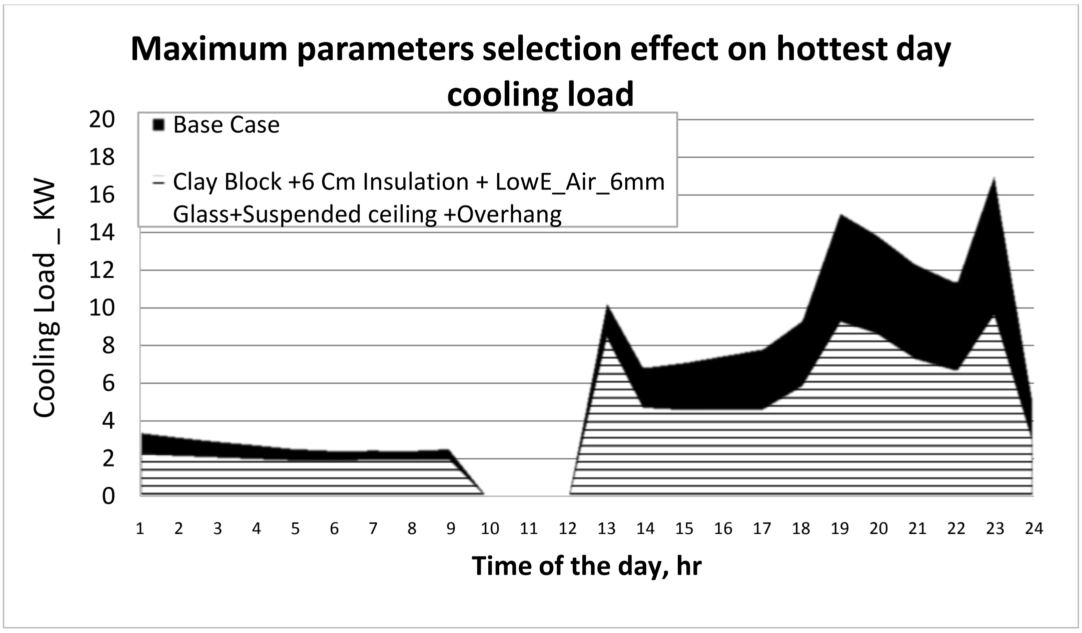


Figure 4-24: Comparison of the house maximum parameters cooling load reduction with the baseline line model in peak hot day

The maximum application of parameters, i.e., the use of clay block, 6 cm thick insulation, lowE-Air-6 mm Glass window, suspended ceiling, and overhang will minimize the annual energy usage from 13104 kWh to 9390kWh over the cooling season from April to October, as shown in Figure 4-24, the reduction represents 28.35% of the overall annual energy consumption and a reduction in building cooling load from 17.47 to 11 kW.

Figure 4-25 shows the annual effect of all parameter's application on cooling load reduction for the house before and after against the base case. This may be considered unduly expensive, whereas with only clay block, 3 cm insulation and suspended ceiling added, the annual energy consumption would become 10142 kWh, equivalent to an annual saving of 22.5%. This had a maximum cooling load of 12.2 kW or a load reduction of 30%. This combination is taken to represent the optimum combination of parameters in the rest of this research.

This modification resulted in a reduction of the load from 17.47 kW to 11 kW, representing a very promising saving in terms of cooling unit's capital cost and the energy used by the system, leading to a reduction in CO_2 emissions.

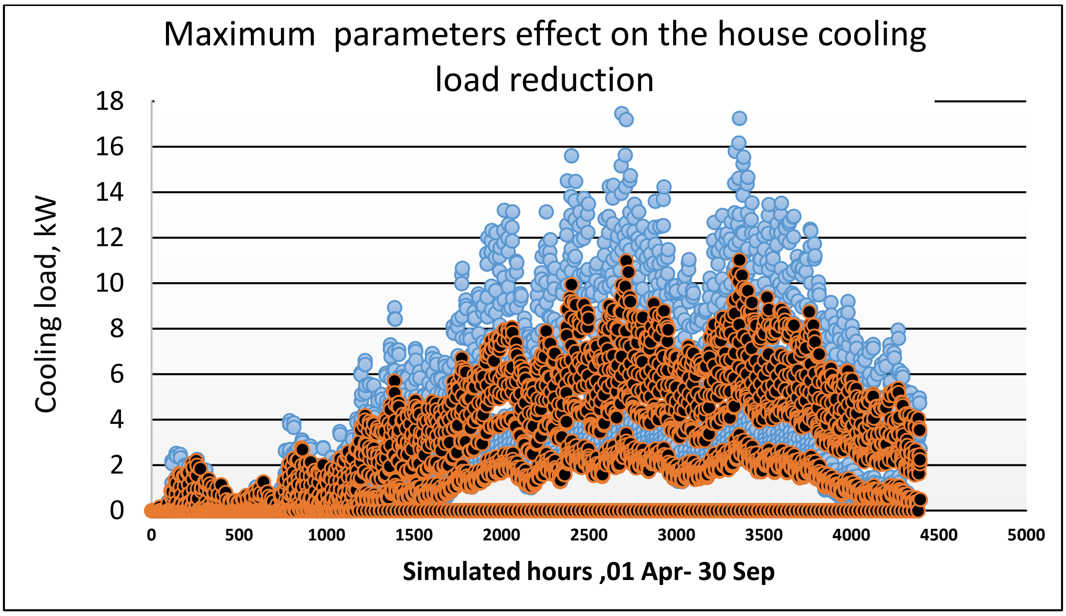


Figure 4-25: Effect of all parameter's application on the house cooling load reduction against the base model

Changing and intervening building fabrication under the same weather conditions, internal parameters and schedules resulted in a large energy-saving without requiring any compromise in human comfort or change in usage schedule of the facilities. Figure 4-26 shows the hourly cooling load profile for six months with outdoor temperature changes. Figure A is the hourly cooling load for the baseline building before applying any improvement parameters, and Figure B shows the cooling load after the adjustments (with all applied parameters); the figure shows an obvious reduction in cooling load after the modifications under the same weather condition.

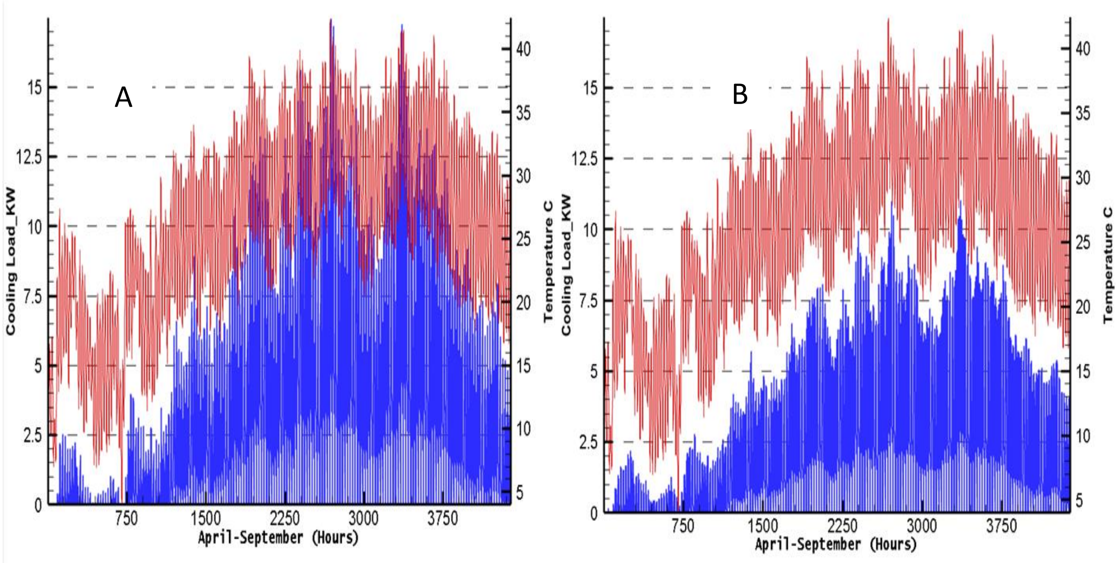


Figure 4-26: Effect of various parameters on cooling load versus external temperature

Figure 4-27 illustrates the hourly-simulated comparison cooling load for the year, it is when adjusting the building with the parameters explained earlier. A comparison of applying of all possible parameters together and just the three most effective parameters which are (clay block, 3 cm wall insulation and the suspended ceiling). The Figure shows that the latter is a better selection for the studied case and doesn't show a big impact of the rest of parameters such as glazing or external overhangs on the cooling load, it could be said the impact is negligible on load reduction.

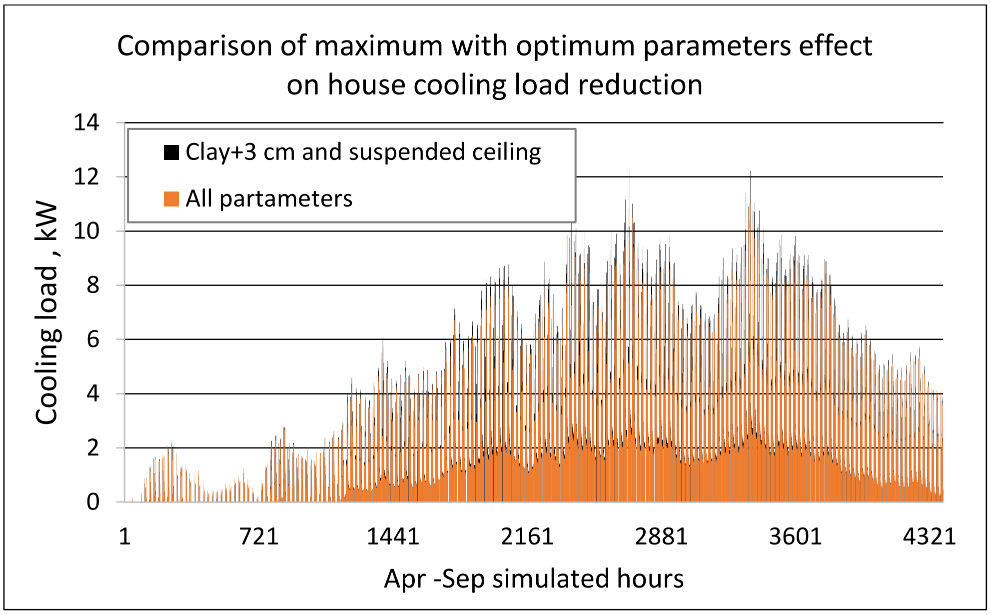


Figure 4-27: All and the optimum parameters effects comparison on the cooling load reduction.

4.2.6.3 Other Total Orientation Effects

The optimum parameters were identified for the South-facing orientation of the case study. Further investigations were undertaken for the other orientations of the building, and then their respective effects on the energy and cooling load. The minimum load and energy consumption were achieved for a North-facing orientation with the same optimum parameters as those of the South. The annual energy consumption was 9274kWh, and the max load was 11.2 kW. This represents a saving of 29.23% in energy consumption compared to the baseline, while the 3 cm and clay block with the suspended ceiling shows a saving of 26.9% and a maximum cooling load of 11.8 kW. This result shows that the glazing and external shading has relatively little effect on the energy and cooling loads for this case as long as the internal shading is in operation and the window/wall ratio is relatively small.

4.2.6.4 Cooling Load Peak Strategy

The cooling load of the building is based on the hourly simulation, combining internal load and external effects due to the weather, because as the weather changes the cooling load fluctuates accordingly. For this reason, the daily peaks have been selected and averaged for the two hottest months. July and August have been used as they are Erbil's peak for two months. Figure 4-28 bottom line (0) represent the average cooling load of 12.44 kW, and the rest of the vertical lines are showing the cooling load day peaks in the building from July-August that won't meet the internal setpoint temperature (25^{0}C) as originally was set to. The unmet loads varied from 0-5 kW as shown in the figure.

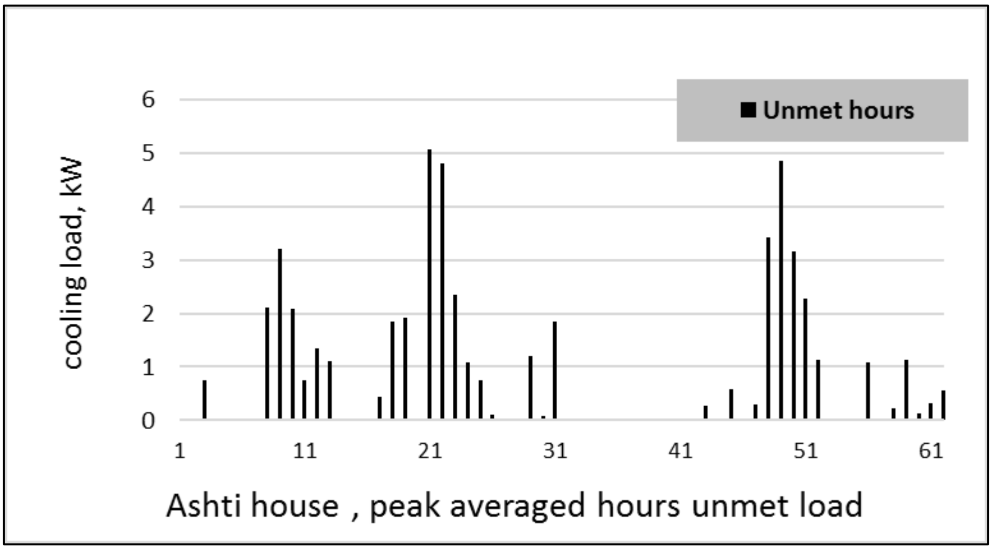


Figure 4-28: Ashti house averaged peak load and unmet load

Using this daily peak average strategy will cover the required cooling loads, as shown in Figure 4-29**,** where 4392 hours cooling load was analysed which represented the house load from April to the end of September. The average peak covers all hours except loads for 46 hours from 13-17 kW, and 29 hours at a cooling load of 11-13 kW. The temperature during the unmet hours, that is when the load exceeds 12.44 kW, will increase to 28-29^{o}C.

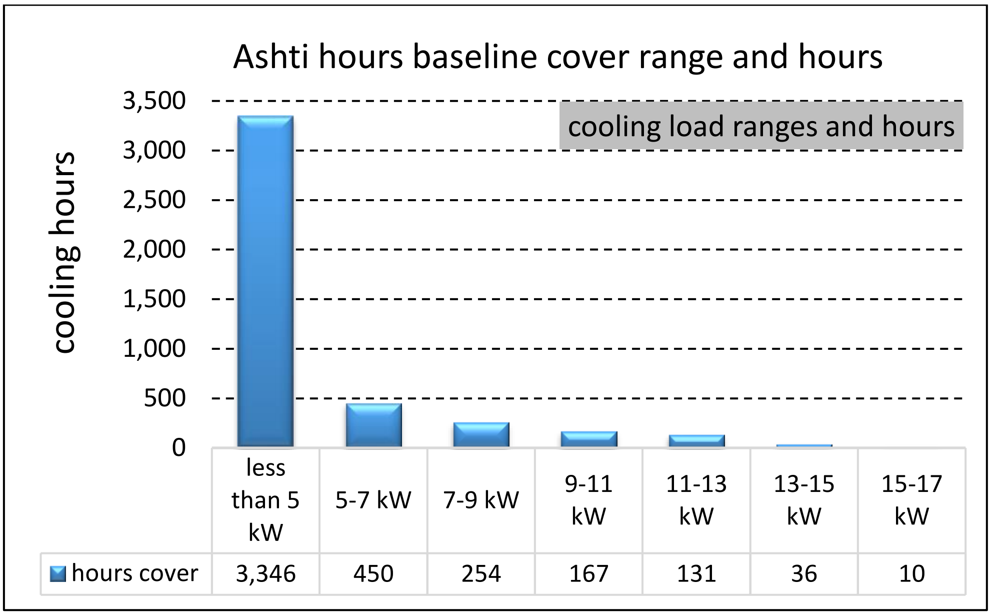


Figure 4-29: Ashti house cooling load range and number of hours

Table 4-6 shows the effect of setting the temperature on the cooling load for the Ashti house and the consequent effect on annual energy consumption on the baseline. As shown in Figure 4-28, the internal temperature rose to 28-29°C when the cooling load was 12.44 kW, and the unmet hours' temperatures for loads between 13-15 kW will be around 27-28°C which would be for 55 hours in July and August and 10 hours between 28-29°C. Hence, if the baseline module was designed with a set temperature of 28°C, the annual energy consumption will be around 8587 kWh.

Table 4-6: Effect of set temperature on cooling load and energy consumption

Set temperature (^{0}C)	Maximum cooling load (kW)	Total energy consumption/year (kWh)
25	17.46	13,105
26	16.0	11,468
27	14.75	9,984
28	13.5	8,587
29	12.3	7,260

According to the literature and ASHRAE fundamentals, raising the internal temperature to above the set or desired temperature will still be within the comfort zone, which for hot zones is in the range 25-28°C [59].

The house unit was examined in detail and analysed in terms of the effects of the various parameters; optimum parameters were found to be the use of clay blocks, 3 cm of insulation and suspended a ceiling, whilst the remainder had no major effects or were not cost-effective if applied. Besides, the cooling load, which will later affect the sizing of a unit, will be reduced, compromising the internal temperatures, as shown and described.

4.3 Case Study 2- Heja City Residential Apartments

4.3.1 Building Details and Construction Materials

The simulation of the cooling load for a low cost, low-rise type apartment building forms case study 2, as described in chapter 3 for low to medium-income families. Heja apartments are a project of eleven similar buildings with the same orientations (South-facing). Each building consists of four levels or floors, each floor consisting of four similar flats with a penthouse at the top of the building, which is used as a service or storeroom in the building. The floor plan of a single apartment has been extracted from the Heja city project, as shown in Figure 4-30.

Figure 4-30: Single apartment floor plan [163].

Each floor consists of four similarly sized flats, each of which consists of two bedrooms, one master bedroom (19.5 m^2 floor area) and a normal bedroom (15 m^2 floor area), a kitchen (12.5 m^2), an entrance hall (12.5 m^2) and a living room (27 m^2). The service zone in the flat covers 14.5 m^2, including the bathroom and a store. The service zone (penthouse) is non-conditioned as it is not cooled. The whole floor plan, including the four apartments, was prepared using the DesignBuilder software, as shown in Figure 4-31, where the dimensions were given to us by the company who completed the project.

Figure 4-31: Floor plan and dimensions of the Heja project

Each flat has two balconies attached to bedroom2 and the kitchen, and as they are not in the thermal zone calculation, they were not considered necessary for the cooling calculations. The building has a corridor with an approximately 70 m^2 floor area that is shared by all four flats on each floor; again, it is a non-conditioned zone, so it was not added or considered in the calculations. This case study model was designed according to the same Iraqi building code. This method of building has been followed since concrete and concrete blocks were introduced into the country some decades ago. The methods of assembly and construction details are shown in Table 4-7, which illustrates the type of materials used, along with the thickness and conductivity of each layer used in the flats construction and assembly. These details were obtained from the brochure published by the executive company and their web site as a secondary data collection process.

Table 4-7: Heja flats construction details

Ground floor	Interior floor-Ground flow	Internal wall-partitions	Ceiling-Floor Floor 2,3,4	External walls	Windows	Doors	Top roof
Cast concrete 30 cm	Local cement Tiles	Gypsum plastering 2 cm	Gypsum 2 cm	Rendering 2 cm	6 mm clear glazing	Painted oak wood	Roof screed 6cm
Soil-ground	Floor screed	Concrete hollow block 20 cm	Concrete Reinforced steel 2%	Concrete hollow blocks 20 cm		Ply wood	Concrete reinforced steel 2%
		Gypsum plastering 2 cm	Floor screed (sand + cement) 10 cm	Gypsum plastering 2 cm			Gypsum 2 cm
			Tiles 2.5 cm				

Further details of the materials used are given in Table 4-8, while the unknown details such as the type of window, frames and external door of the building are assumed according to the availability of materials and experts’ recommendations. For example, vinyl was chosen for the window frame material and metal for the external door.

Table 4-8: Construction materials and thicknesses used in the flat building [164]

Material Name	Thickness cm (cm)	Conductivity W/m.K	Density kg/m³
Earth soil	40	1.28	1460
Cast concrete	30	1.13	2000
Concrete block Hollow	20	1.35	1220
Clay block	20	0.3	1000
Floor screed	10	0.41	1200
Floor tiles	2.5	2	2243
Concrete reinforced steel 2%	25	2.5	2400
Rendering	2	1	1800
Gypsum plastering	2	0.4	1000
Plywood	0.6	0.15	700
Roof screed	6	0.41	1200

Following the floor plan received from the project, the DesignBuilder software was employed to model and design the base case mode of the flat, and was loaded with all relevant construction information from Table 4-7 and Table4-8 to represent the actual building fabrication parameters.

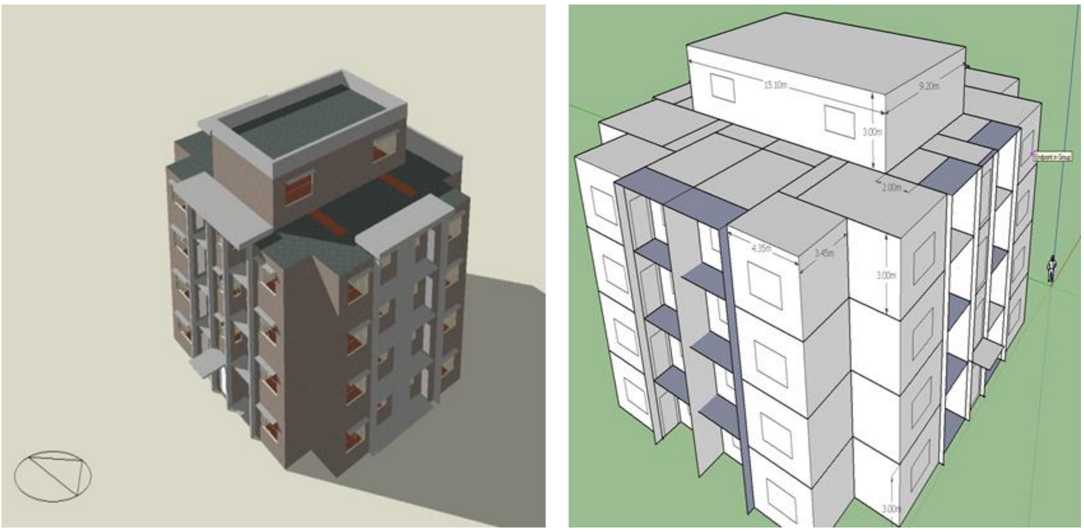


Figure 4-32: Heja apartment block modelled by DesignBuilder

The building, as shown in Figure 4-32 includes four different schedules from what will be referred to as Flats A, B, C, and Flat D as shown in Figure 4-33. This represents multiple families' effects on cooling in the building. All four flats are located on the building corners, each one of which has two side façades. Going clockwise, Flat A faces South-West, Flat B faces North-West, Flat C faces South-East, and Flat D faces North-East.

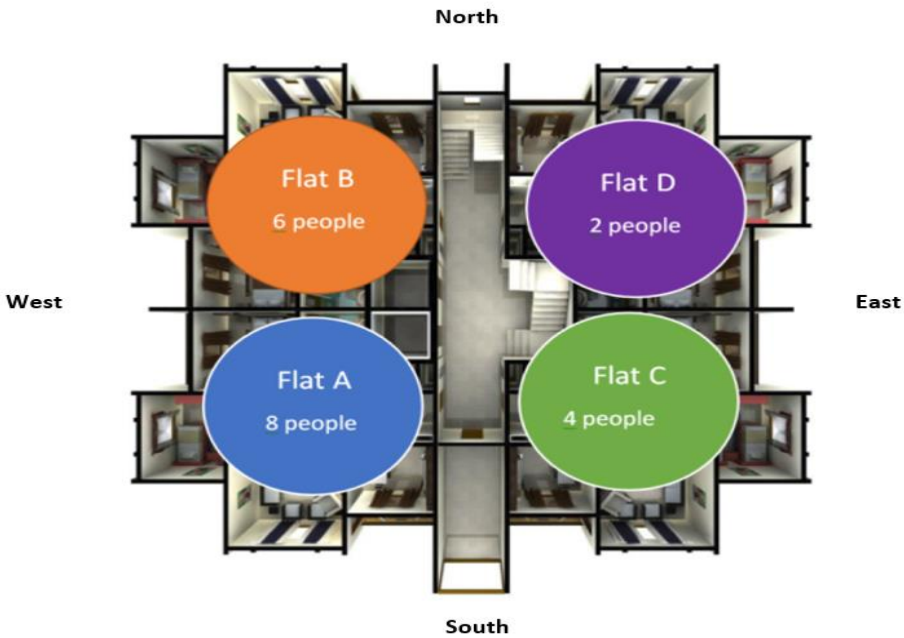


Figure 4-33: Heja flat Floor distributions and thermal zones of the four flats, location and occupancy for each flat/floor.

4.3.2 Internal Parameters, Activities, and Schedules

According to the floor plan mentioned earlier, each one of the four apartments has seven thermal zones consisting of two bedrooms, a living room, a kitchen, hall, bathroom, and a store. All these zones are similar in size for all four apartments, as illustrated on the project map, Figure 4-30. This case study concentrates only on the cooling demand in this type of building. The uncooled, unconditioned spaces such as the bathroom and the store are combined into a single zone referred to as the service zone, whilst the main corridor is not considered in the cooling assessment calculation.

The case study flats modelled were labelled Flats A, B, C, and D to allow their differentiation for the load calculations. The building was loaded with different internal parameters according to four different family categories; a large family, two working medium-sized families and a small working family (a couple), with different availability in the building. The schedules kept by the various occupants in each flat scenario reflect different patterns of Kurdish family life. The dates on which the occupants are present, and usage with cooling settings in each flat zone are illustrated in Table 4-9.

Table 4-9: Occupancy number/rate per flat and weekday occupancy schedules for Flats A, B, C, and D.

	Flat A	Flat B	Flat C	Flat D
No of people	8 Four adults Four children	6 Two adults Four children	4 Two Adults Two children	2 Two adults only
Cooling operating schedule	7 days	7 days	6 days	5 days
Cooling internal set temperature	25°C	25°C	25°C	25°C
Cooling system type	Split systems	Split systems	Split systems	Split systems

Referring to the main issues of housing needs reports from the United Nations HABITAT [156], some Kurdish families' living spaces are overcrowded; this can be for various reasons, such as tradition and income issues. The model for Flat A was scheduled to occupy four adults and four children. Although adulthood is considered to start at eighteen years old, a person in a traditional Kurdish family would stay and live with his parent until he/she gets married or may even sometimes remain with the family after marriage for many years. Flat A was loaded with the schedule given in the first column of Table 4-9**.** It is heavily occupied all seven days of the week according to the schedules used in the modelling software.

The lighting intensity and the power consumption in the building are mainly dependent on the lighting installed. The normal practice in Iraqi residential buildings is to use long florescent tube-type lights, and they are normally fixed to the ceiling. The power intensity was calculated to be around 8 W/m^2 for all flat areas in the large zones, and this rate is much higher due to the power/floor area in smaller zones, such as the bathroom and the store, because the power is divided according to floor area, W/m^2, but this is not calculated as it is not included in the cooled thermal zones. The lighting is used according to the schedules depending on the type and nature of the lighting requirements for each zone. The heat that the appliances generate in the residential buildings could be very high, resulting in increased use of the air conditioning, and thus increased energy consumption. Estimating the right number of appliances in a building is very important to the calculations.

Each zone in the Flats A, B, C, and D are loaded with different appliances and schedules, such as radio, TV, computer, fridge, cooker, etc. The appliance's power ratings according to the inputs are between 2-5 W/m^2 /zone multiplied by the usage factor and the schedule input details [45]. The heat produced is mostly from the kitchen, and it is 20 W/m^2 for flats C and D, 23 W/m^2 for flat B and 28 W/m^2 is for Flat A. Bedrooms have no appliances or any electrical equipment. Table 4-10 shows the schedules and activity for each flat’s zones.

Table 4-10: Flat A, B, C, and D occupancy, lighting, equipment's schedules

Flat A	Occupancy	Lighting	Equipment	Activity (metabolic) W/person
Kitchen	9:00 – 13:00 18:00 – 21:00	10:00 – 21:00	Until 9:00 0.2 Until 13:00, 1 Until 18:00, 0.2 Until 21:00, 1 Until 00:00, 0.2	Cooking and eating
Hall	12:00 – 23:00	14:00 -00:00	12:00-23:00, 0.5	Minor house work
Bed1	00:00 – 8:00 14:00 – 17:00	8:00 – 00:00 17:00 – 23:00	--	Resting / sleeping
Bed2	00:00 - 8:00 14:00 – 17:00	8:00 – 12:00 17:00 – 23:00	12:00-22:00, 0.5	Resting /sleeping
Living	14:00 – 18:00, 0.5 18:00 – 21:00	14:00 – 00:00	12:00 - 22:00	Sitting / reclining
service	8:00 – 10:00 12:00-14:00 18:00 – 20:00	12:00-23:00	11:00 – 14:00	Sitting quietly /light work
Flat B	**Occupancy**	**Lighting**	**Equipment**	**Activity (metabolic) W/person**
Kitchen	8:00-10:00 12:00-14:00 20:00-22:00	12:00-00:00	00:00-8:00, 0.2 8:00- 13:00, 1 13:00-18:00, 0.2 18:00-21:00, 1 21:00-00:00, 0.2	Cooking and eating
Hall	12:00-23:00	12:00-24:00	12:00-18:00, 0.5	Minor house work
Bed1	22:00-7:00	13:00-23:00	--	Resting / sleeping
Bed2	22:00-7:00	13:00-23:00	21:00-00:00	Resting /sleeping
Living	9:00 – 16:00 19:00 -22:00	13:00-23:00	12:00-22:00	Sitting / reclining
Service Bath & store	7:00-10:00 18:00-22:00	12:00-23:00	10:00-14:00	Sitting quietly /light work

Flat C	**Occupancy**	**lighting**	**equipment**	**Activity (metabolic) W/person**
Kitchen	7:00 - 9:00 16:00 - 18:00 21:00 - 22:00	16:00 - 22:00	7:00 - 9:00 17:00 - 20:00 Then 0.2	Cooking and eating
Hall	16:00 - 22:00	16:00 - 22:00	16:00 – 20:00	Minor house work
Bed1	22:00 -7:00	16:00 - 22:00	7:00 – 9:00 21:00 -23:00	Resting / sleeping
Bed2	22:00 - 7:00	16:00 - 22:00	7 :00- 9:00 21:00 - 23:00	Resting /sleeping
Living	16:00 -22:00	16:00 - 22:00	16:00 - 22:00	Sitting / reclining
Service Bath & store	7:00 - 10:00 18:00 - 22:00	7:00 - 10:00 16:00 - 22:00	16:00 - 20:00	Sitting quietly /light work
Flat D	**Occupancy**	**Lighting**	**Equipment**	**Activity (metabolic) W/person**
Kitchen	7:00 - 9:00 17:00- 19:00	16:00 - 24:00	00:00-16:00 ,0.2 16:00-20:00, 1 20:00-00:00,0.2	Cooking and eating
Hall	17:00 -23:00	16:00 – 00:00	16:00- 20:00	Minor house work
Bed1	Not occupied	--	--	Not used
Bed2	23:00 – 8:00	16:00 -00:00	16:00-22:00	Resting /sleeping
Living	17:00-23:00	16:00 – 00:00	16:00-00:00	Sitting / reclining
service	8:00 – 9:00 17:00-18:00 21:00-22:00	18:00-22:00	7:00 - 8:00 20:00 – 22:00	Sitting quietly /light work

4.3.3 Cooling Supply Times and Scheduling

All of the Heja building flats were loaded with similar schedules; however, the concentration is only on the first floor, leaving the ground and top floor separate, as, assuming there is no effect from the top or bottom buildings, which reflects on most buildings of a similar type. Following the same procedure that was done for the Ashti city unit to schedule the operation times of flats (A, B, and C). Assumptions were made for lighting and the internal equipment operation times and over phone enquiries for the cooling supply times in the flats from the occupants. However flat D scheduling totally based on assumptions, as the occupants were new married working couples and were available to communicate.

Flats A, B, C, and flat D were loaded with different cooling supply timing schedules to reflect and maintain the comfort of the occupants in zones while they are occupied and conditioning is needed Table 4-11 is the cooling schedules in each flat with the timing. Similar to Table 4-10 is the four flats scheduling of the internal parameters, such as occupancy.

Table 4-11: The cooling supply schedules and set times per zone

Flat A	Cooling supply hours from: 01/04 to 30/09 of the year
Living room	11:00 - 23:00
Bed1	22:00 - 8:00, 14:00 - 17:00
Bed2	22:00 - 8:00, 14:00 - 17:00
Hall	11:00 - 23:00
Kitchen	11:00 - 23:00
Flat B	**Cooling supply hours from: 01/04 to 30/09**
Living room	12:00 - 22:00
Bed1	22:00 - 7:00
Bed2	22:00 - 7:00
Hall	12:00 - 22:00
Kitchen	12:00 - 22:00
Flat C	**Cooling supply hours from: 01/04 to 30/09, (No cooling on Fridays)**
Living room	16:00 - 24:00
Bed1	16:00 - 7:00
Bed2	16:00 - 7:00
Hall	16:00 - 24:00
Kitchen	16:00- 24:00
Flat D	**Cooling supply hours from: 01/04 to 30/09, (No cooling on Thursdays and Fridays)**
Living room	16:00 - 24:00
Bed1	No cooling or occupancy
Bed2	22:00 - 8:00
Hall	16:00 - 24:00
Kitchen	16:00 - 24:00

The cooling load for each zone in the building was calculated separately (load/zone) according to the associated requirements and cooling supply schedules, taking into consideration the hourly external heat gain effects from the weather data, which was then added to the internally produced heat due to the occupants, lighting, and equipment. The building shell plays a significant role in increasing the cooling load of a given zone as it transfers heat from outside the building into internal zones. This rate of heat transfer depends on the properties, such as conductivity (U-value), of the materials used in the construction. The lower the conductivity of the material, the less heat transferred into the internal zones.

4.4 Cooling Load

Each flat involved in this study has seven separate zones, five of which are conditioned and cooled with a set internal air temperature of 25°C. An hourly cooling load was calculated separately for each zone using the EnergyPlus software, where the cooling used was according to the schedules and usage requirements of each family, as shown in Table 4-11. The hourly cooling loads calculated for each of the five zones in each flat was combined as a total load on an hourly basis. Each flat was simulated for six months' worth of hours, so the model ran 4392 hrs of simulation from the 1st of April until the 30th of September, which is the typical cooling season and when air conditioning is required. July and August are the hottest months in Kurdistan, and the peak times begin around the middle of July when the ambient temperature can reach 45°C at noon.

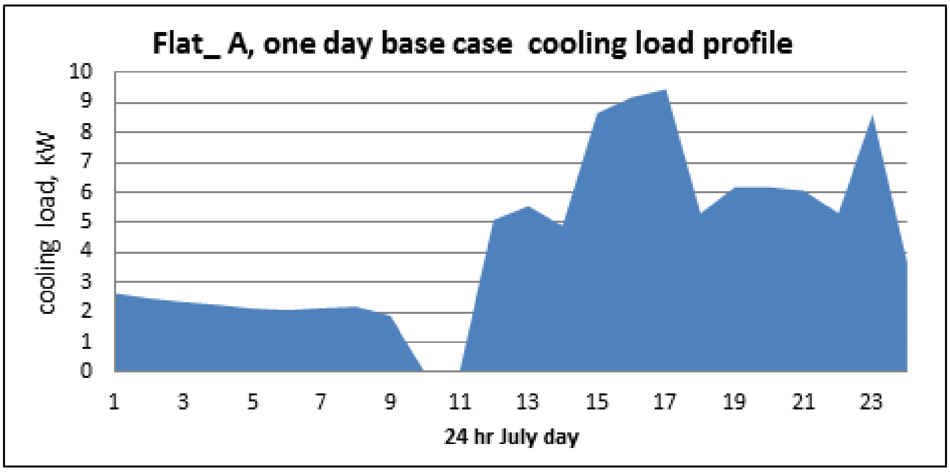
4.4.1 Individual and Combined Flats Cooling Loads

4.4.1.1 Flat A

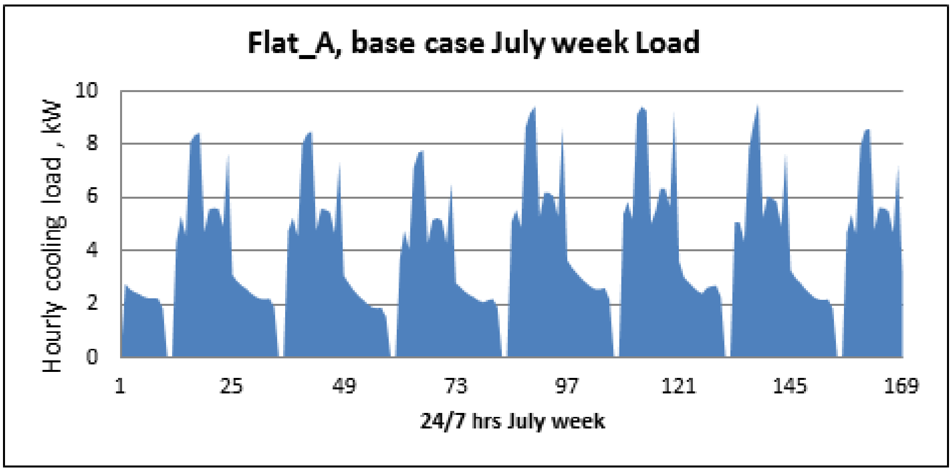
Figure 4-34 illustrates the hourly-simulated cooling load profile for a day, a week and the whole month of July. Figure 4-34A shows the hourly-simulated cooling load for the peak day of 21st July (hottest day of the year), the flat is originally facing South-West, running from 1:00 to 24:00. The profile load pattern reflects the cooling supply and required schedules shown in Table 4-11. From 24:00 until 8:00 the air conditioning in the two bedrooms is on, while the remaining zones are off, as reflected in the cooling profile by the fact that the cooling load does not exceed 3 kW during sleeping hours. From 8:00 until 11:00 there is no cooling operated in the flat A and later restarts in the other flat zones, starting from 11:00 to 14:00 the cooling load for the combined hall, kitchen and living areas showing to be around 5.5 kW. From 14:00 to 17:00, when all zones are cooled, the cooling load reaches its maximum to 9.5 kW at about 17:00, which is expected because the ambient temperature is very high during this time of the day. With the maximum overall cooling load of 9.5 kW in the peak day of the year. The total cooling load/area was found to be 110 W/m^2 for the overall of flat A floor area.

The cooling load for all zones at 23:00 is 8.5 kW, this is less by 1 kW for the same zones peak at 17:00. This is when the ambient temperature drops and in the absence of the sun radiation's effect on the building, however, each flat has only two sides open to the ambient temperature as the calculated cooling load is only for the middle first floor of the flat, as there is no effect from the ground or top floor.

Figure 4-34B shows the hourly cooling profile for the peak week in July (from 18th to 24th July). The profile for each day of this week is very similar to the peak day cooling profile, as shown in Figure 4-34A because cooling supply schedule is the same each day, but the peaks are different due to the difference in external weather conditions such as temperature, air velocity and solar gain. Figure 4-34C shows the hourly cooling profile for the whole month from 1st to 31st July, covering 744 hours of simulation. The cooling profile includes 31 profiles that are essentially similar to the peak day. The 5$^{th\ of}$ July shows the lowest peak load of 5.5 kW.



A



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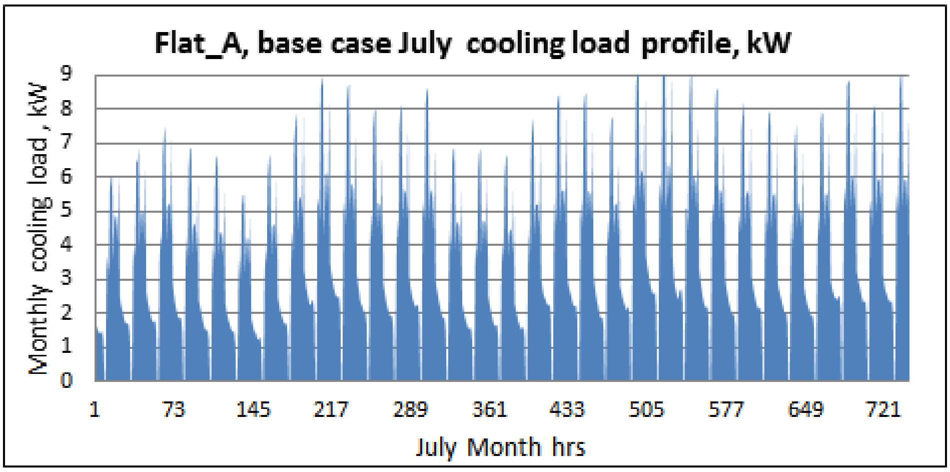


C

Figure 4-34: Flat A cooling load profile

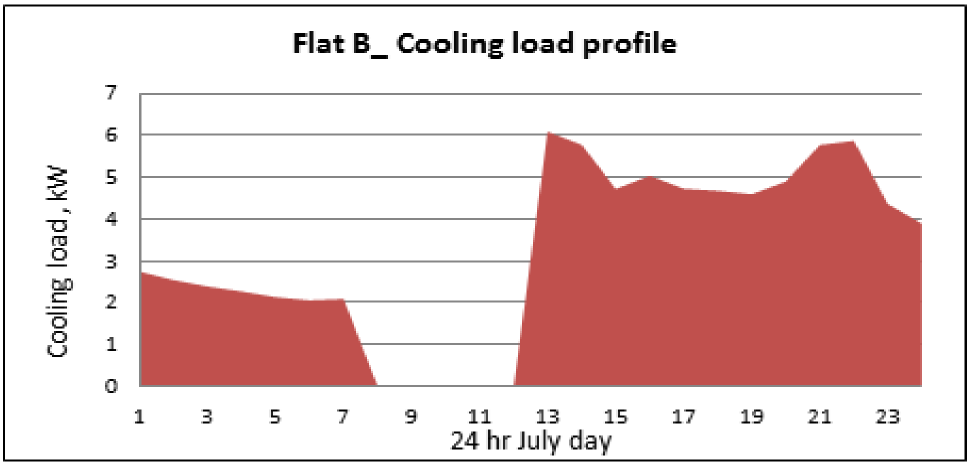
4.4.1.2 *Flat B*

Figure 4-35 shows the hourly simulated cooling profile pattern for the second flat that is originally facing North-West; this flat is occupied by six people. Figure 4-35A is a 24-hour simulation for the 21st July (the hottest day) starting from midnight 00:00. This profile reflects the cooling requirement for each zone to reach 25° C. The pattern is for cooling usage in flat B according to the selected cooling supply schedule shown in Table 4-11. From 22:00 until 7:00, cooling is required in bedroom 1 and bedroom 2. When cooling in the bedrooms starts at 22:00, the cooling load is 4.3 kW; this gradually reduces to 2.08 kW at 7:00 and is at its maximum at 22:00. Then, from 7:00 until 12:00, there is no cooling operating in the flats. Cooling starts again in other zones, such as the hall, kitchen and the reception, from 12:00 until 22:00.

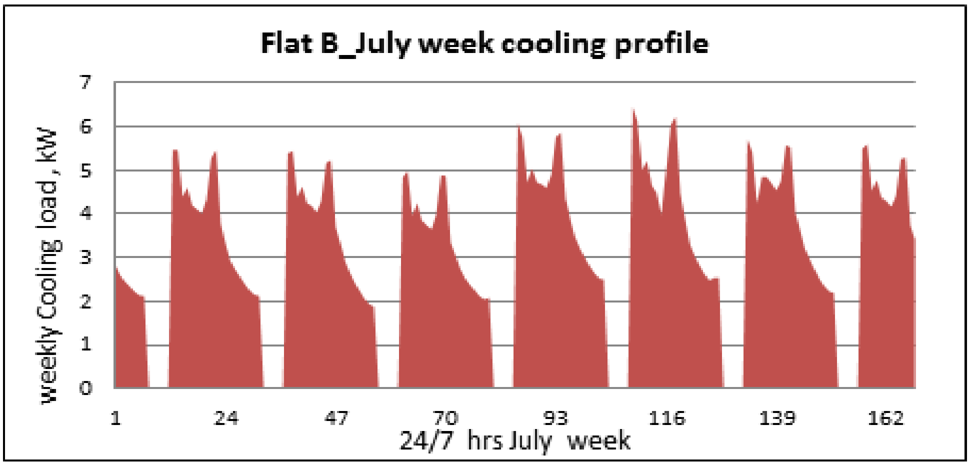
Cooling in the hall, kitchen and living area reaches a peak of 6.1 kW at 12:00 due to the accumulated heat in these zones and the fact that the cooling was off for about 5 hours, so it decreases then reaches the maximum again from 20:00-22:00, then it switches to only two bedrooms with cooling load of 4.36 kW.

Figure 4-35B is the simulation of the hottest week of the year. The graph shows three days before 21st July and three days after. Although it was mentioned that the hottest day is the 21st, according to the graph it is the 22nd of July as the load is slightly higher as at its peak it reaches 6.44 kW. This is a reflection of the location (orientation) of the flat in the building. The maximum cooling in Flat B fluctuates between 4.98 to 6.44 kW for the three zones. Although the cooling was operating in the flat for most of the day, the two bedrooms and the kitchen, and the hall and living zones did not cool at the same time.

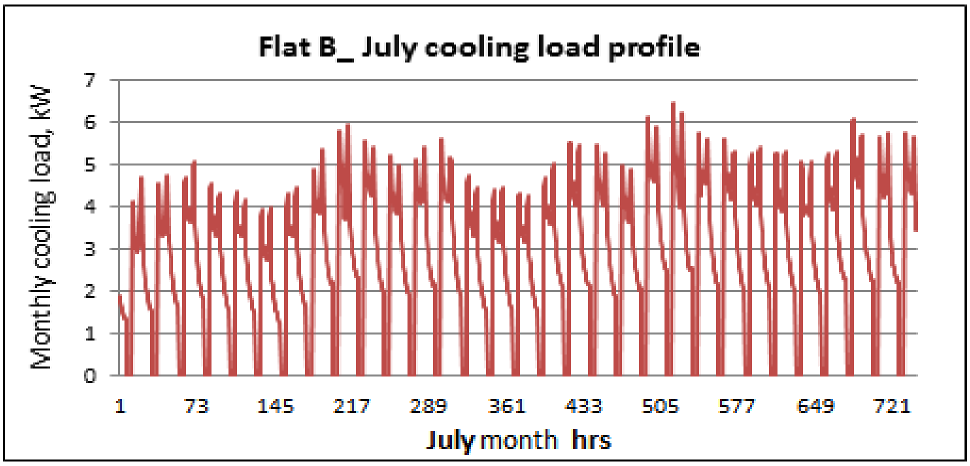
Figure 4-35C shows the hottest month in Erbil for flat B, which illustrates 1st – 31st July, this is the hourly pattern of 744 hours, which is the multiple repetitions of Figure 4-35A it shows the maximum cooling load in the flat of 6.44 kW at 12:00-13:00 day time in the hottest week of July.



A



B



C

Figure 4-35: Flat B peak day, week and hottest month cooling load profile

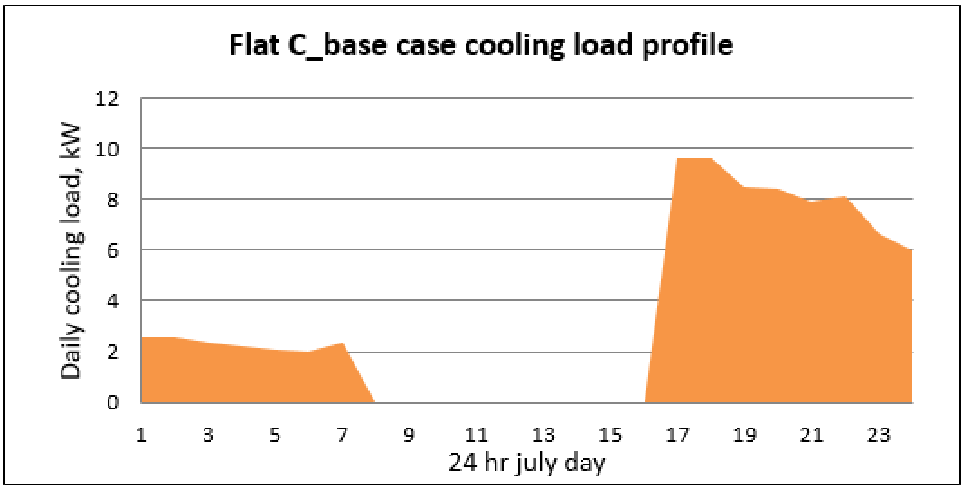
4.4.1.3 Flat C

Figure *4-36* represents the hourly-simulated results over a total of 744 hours for Flat C that faces South-East. *Figure 4-36A* shows the combined hourly simulation of the cooling load for Flat C for the peak day in July, as per the cooling schedules are given in Table 4-11. There are four occupants in this flat, two adults and two children, which is a small family compared to flat A, which is overcrowded, and Flat B, with its six occupants. Cooling in bedroom 1 and bedroom 2 was in operation from midnight 0:00 hrs almost every day, apart from Fridays when the cooling is off for the entire day. However, for the remaining of six days, starting from 00:00 and running until 7:00, after which it is off until 16:00 when the flat is occupied again, and the cooling is in operation in both bedrooms until the next day at 7:00. The cooling load for both rooms combined was found to be 2.578 kW, which then reduced to 2.02 kW at an early time in the morning then rises to 2.33 kW again. This gives a difference in cooling load of 0.55 kW between midnight and early morning due to the absence of solar radiation and temperature variations during the day. The kitchen, hall and living areas are cooled from 16:00 until 0:00 reaching a peak at around 16:00-17:00 and slowly reduces until midnight. when it reaches a high as 6 kW, the cooling load is high due to the cooling operation at all zones, including the two bedrooms that started cooling from 16:00 as shown in Table 4-11.

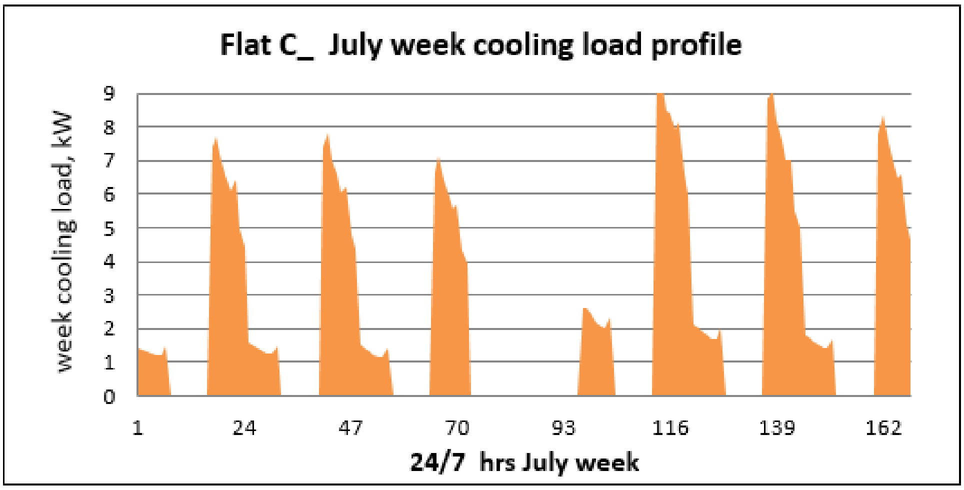
The one-day pattern in Figure *4-36* A is for the 22nd July rather than 21st, as it was scheduled that the family had a day out (Friday) and no cooling was used in the building. The cooling load reached its maximum between 16:00-17:00 of around 9.6 kW, due to all five zones in the flat being cooled at the same time too, it is gradually reducing until midnight when it reaches just under 6kW for all zones, this is showing only 3.87 kW for other three zones together.

Figure *4-36*B is the weekly load profile of Flat C, when the calculation of the load starts from 00:00 the load is small because it represents only two bedrooms and is around 2.5 kW until 7:00, after that when all zones cooling system is off until 16:00, then cooling restarts until midnight. The middle of the graph is the Friday, when the family members are out, so no cooling was used, the graph shows a repetition of every day cooling load pattern based on outside weather conditions and keeping the internal heat gain unchanged. The load is at a maximum towards the end of July, which is very understandable as the end of July and beginning of August represent the hottest period of the year in Kurdistan.

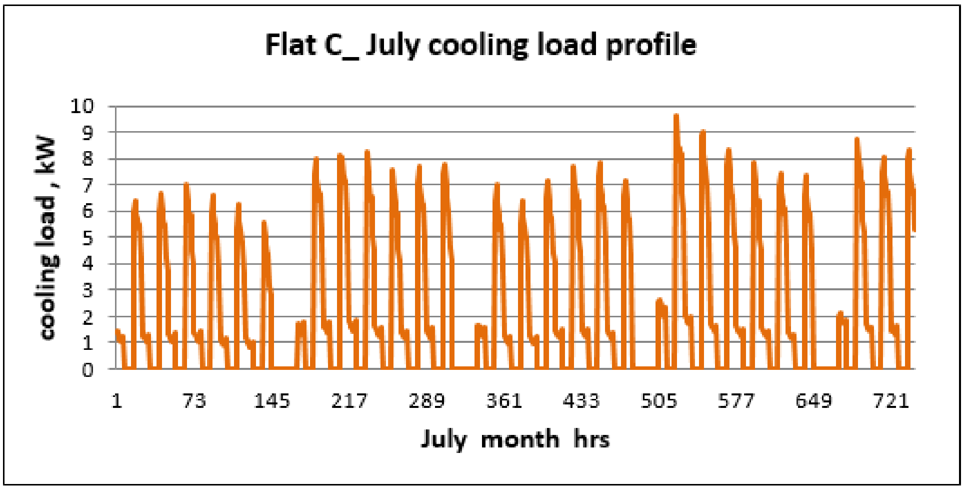
Figure *4-36*C represents the hourly simulation for 1st - 31st July, covering 744 simulated hours. It is effectively a replica of Figure *4-36*A, showing the effects of external weather conditions on cooling load when the internal parameters that add heat were kept unchanged. The cooling load increased towards the end of the month and reached a maximum of 9.6 kW.



A



B



C

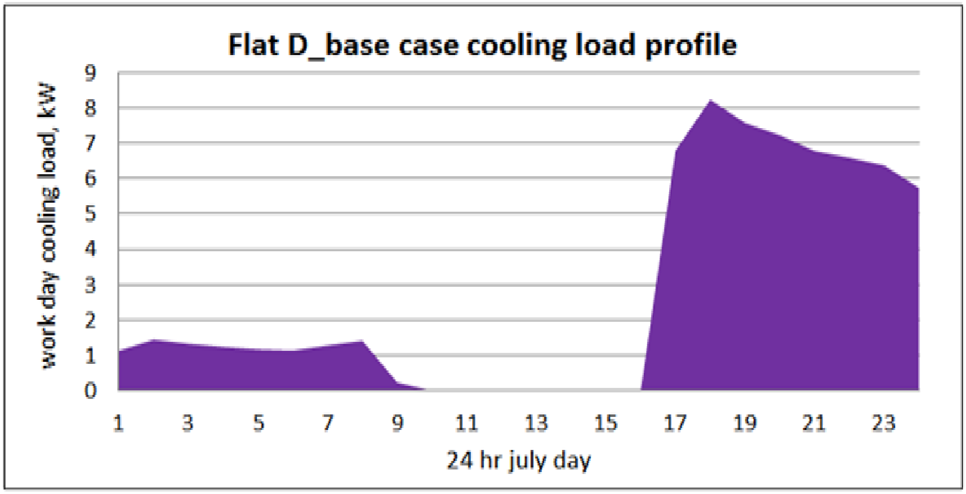
Figure 4-36: Flat C peak day, week and hottest month cooling load profile

4.4.1.4 Flat D

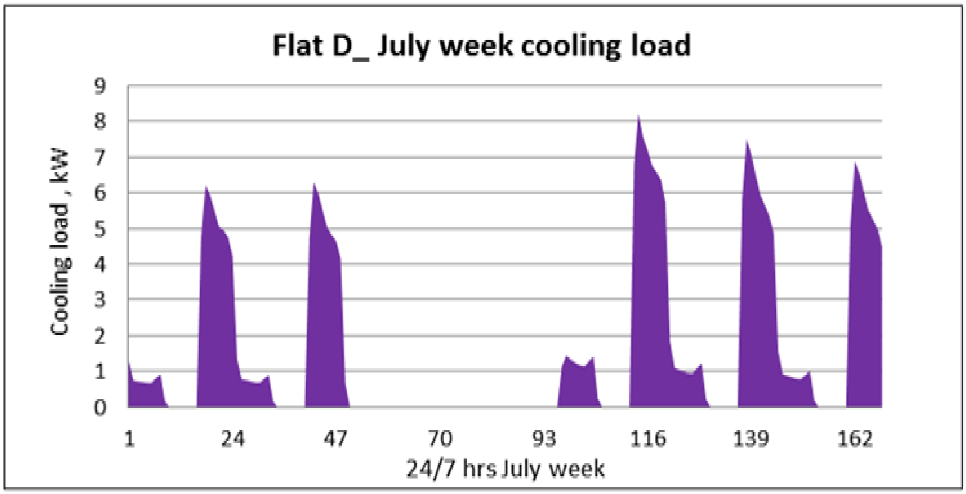
Figure 4-37 shows the hourly cooling load pattern in Flat D that faces North-East, where the three graphs representing a day, a week and the month of July. This profile is for a small family of two working adults or a married couple Figure 4-37 A represents a 24-hour cooling load profile, starting from 00:00 in one bedroom as the 2nd bedroom in the flat is not cooled. The low cooling load is relatively small 1.13-1.4 kW until 8:00, and then from 8:00 until 16:00, all the cooling systems were switched off in all zones. Cooling restarts from 16:00 in all zones apart from bedroom 1, and the load increases until reaching a peak load at 8.22 kW between 16:00-17:00. This is high because of the heat that has been accumulated in the flat during the day times, and also the effects from the ambient conditions, then the load is reduced from peak to a total of 5.73 kW for all four cooled areas. Separating the bedroom load from the other three zones would make the total cooling for kitchen, hall, and living as low as 4.5 kW. Although it was noted that the hottest day of the year is the 21st July, in this simulation the load is zero because it is Friday and all the cooling systems are off in the flat D, this is why the plots are for the next day, the 22nd July.

Figure 4-37B shows the weekly cooling profile for flat D. From Table 4-11, it can be seen that on Thursdays and Fridays the flat is unoccupied, and no cooling is used in the building. The weekly cooling profile is for 168 simulated hours from 18th-24th, or the hottest days of July. It shows that the peak load is only for a very few hours and is not repeated, although the pattern is essentially the same because of the repeated schedule.

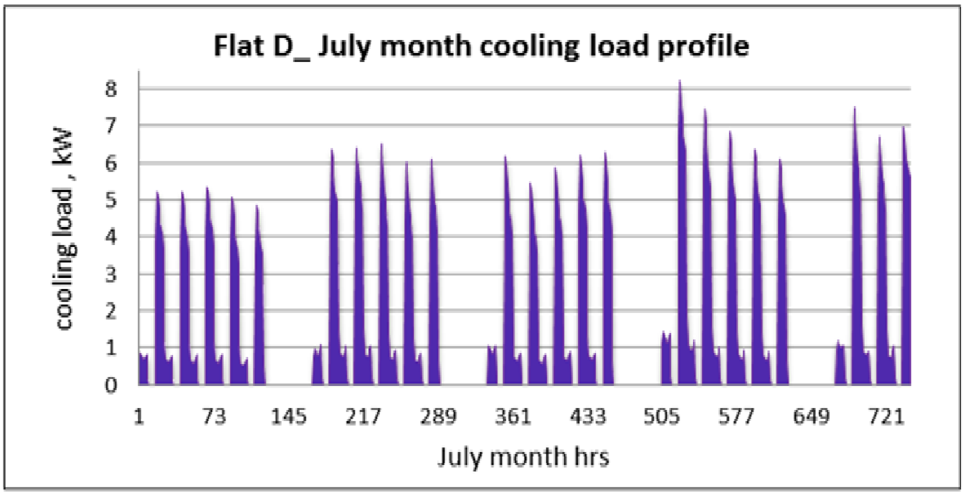
Figure 4-37C illustrates July's cooling profile, which is 744 simulated hours from 1st-31st. It starts with bedroom 2's cooling load reaching the peak of the day at 18:00-19:00 because all four zones are cooling at the same time. The slots in the graph show the cooling systems are not operating in the building. The maximum cooling was towards the last weeks of July.



A



B



C

Figure 4-37: Flat D peak day, week and hottest month cooling load profile

4.4.1.5 Total Combined Load of Flats

Figure 4-38 represents the hourly simulation of four combined flats in one profile for one hot July day, the hottest week and July itself. The profiles shown are in accord with the operations and supply times of the cooling systems that are required in each flat (A, B, C and D). Here, the overall profile for 22nd July was selected, as it is the most frequently repeated load profile pattern. Five days of the week have this cooling load profile pattern, regardless of its actual magnitude, whilst the other two days, such as Thursday and Friday, affect the weekly profile and indeed for Flat C and Flat D are turned off.

Figure 4-38A is the peak day of July covering all flat zones for 24 hrs; this simulation results obtained from the EnergyPlus. It covers from 00:00 to 8:00-9:00 for seven bedrooms (three of bedroom one and four of bedroom two) the load starts at 10.5 to 8.6 kW and then decreases to 4 and 2.4 kW as the cooling system is switched off in some bedrooms, as per the selections and cooling schedules used in EnergyPlus. Then the whole cooling system is off between 9:00-12:00, starting again at 12:00 and gradually increasing until it reaches a peak of 30.34 kW at 17:00. This represents the maximum cooling load for the first floor of Heja building, the cooling load in the floor stays almost in the same range and reduces to as low as 25.56 kW until midnight, then declines to 19.2 kW when most zones are off.

Figure 4-38B represents the combined cooling load for the hottest week of the year at the end of July. The profile shows 168 hourly-simulated results from EnergyPlus, where the internal parameters kept unchanged and internal set temperature of 25^{o}C is maintained. The profile also shows the peak for each day from 18th -24th July to be around 25, 24.8, 18.2, 14.22, 30.34, 29 and 25.8 kW, respectively. The cooling load is 18.2 kW on Thursday when Flat D cooling system is not operating, and where the 14.22 kW load represents Flat A and B only, as on Friday both flats C and D switch off their cooling. The peak load in the total floor flats in July reaches its maximum at 30.34 kW. This profile was obtained using the supply schedule in Table 4-11.

Figure 4-38C is the July cooling profile, which is a result of 744 hours of simulation using the weather conditions and details from Erbil city. The load pattern fluctuates, as shown in the figure. This profile is a useful tool for designing the cooling system for the building in order to provide adequate cooling to all zones on the floor or to use the load as a reference to estimate similar building loads and designing their cooling systems accordingly to avoid oversizing and minimizing energy waste.

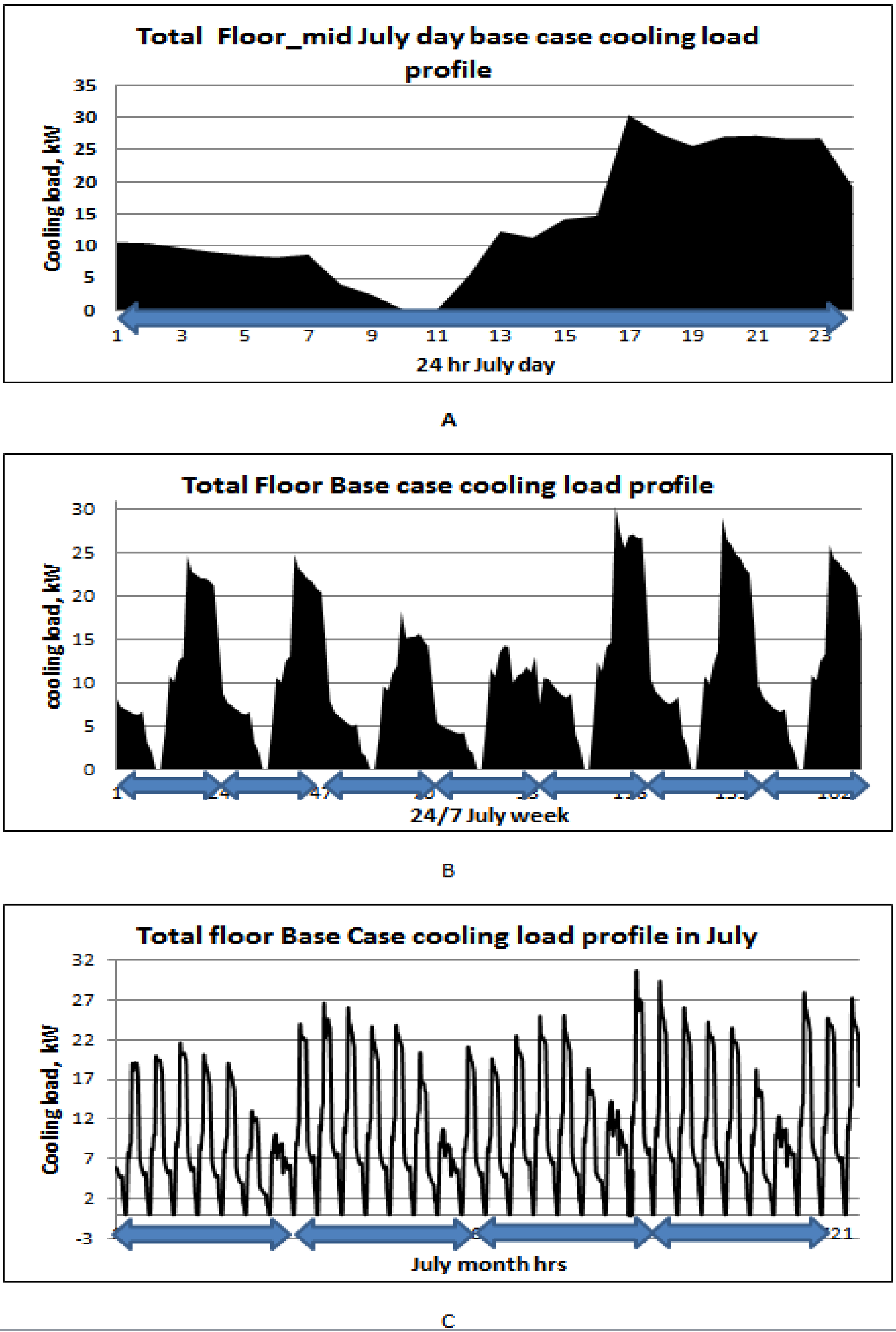


Figure 4-38: Combined cooling load profile for all flats.

4.4.2 The Primary Results of the Baseline Module

The primary results for the baseline flats together with the simulated season running from April to October indicated that the greatest part of the energy consumed in the building was used by the cooling system (79%) to reach the desired set temperature of

25°C. Other electrical equipment uses (7%), then the lightings consumed (14%) was as shown in Figure 4-39. This is a very similar percentage to the house cooling load illustrated earlier with different effects from the equipment and lighting.

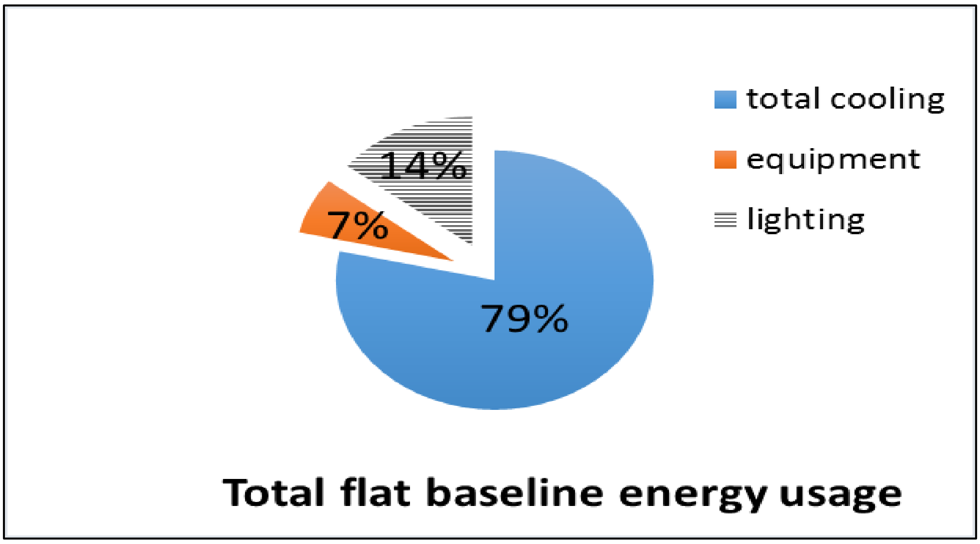


Figure 4-39: Total energy consumption of the flats

Figure 4-40 shows the cooling load for each flat and floor in the building, where here the studied case is the 21st floor as explained earlier; however, the cooling load increases with the height of the building, with the top floor being directly exposed to solar irradiation.

The percentage of floor/total load in the flat is 22% for the ground floor, 1st floor 23%, 2nd floor 24.6% and the top floor is 29.5%, where the whole building's baseline is 144.2 kW.

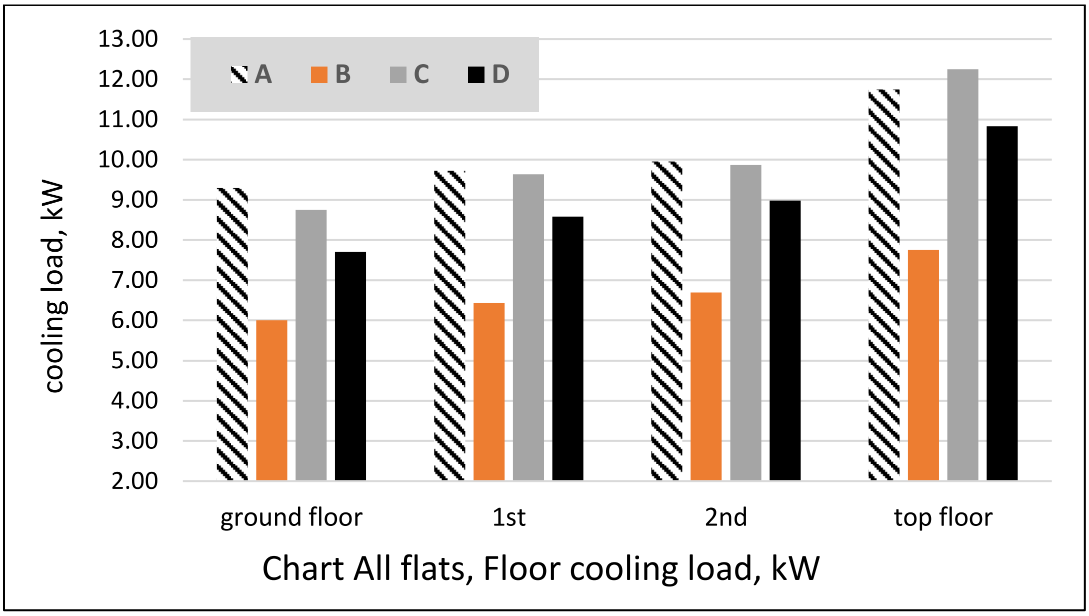


Figure 4-40: Peak total cooling load for all floors of the building

4.4.3 Impacts of the Different Parameters

The annual cooling energy (kWh), and the cooling load (kW) were simulated for the baseline module for the Heja flats, where each of the four flats was separately considered to assess the cooling energy consumed and the cooling load. An EnergyPlus simulation was run for each parameter alone whilst keeping the rest unchanged to assess the effect of individual parameters on both cooling energy and load without the interference of the others on the baseline. These analyses were undertaken with due consideration for the orientations of each section of the flats. The simulations tested the same parameter combinations as for case study 1, though for reasons of space the effects are combined in a single graph for the flats where they show similar findings as for the house.

4.4.3.1 Impacts of the Different Parameters on Flat A

Flat A was simulated with the following baseline details: the annual energy consumption was 8621.5 kWh, and the maximum cooling load was 9.73 kW. After applying the different parameters separately, cooling energy and load were changed by different amounts by the various parameters tested, as shown in Figure 4-41.

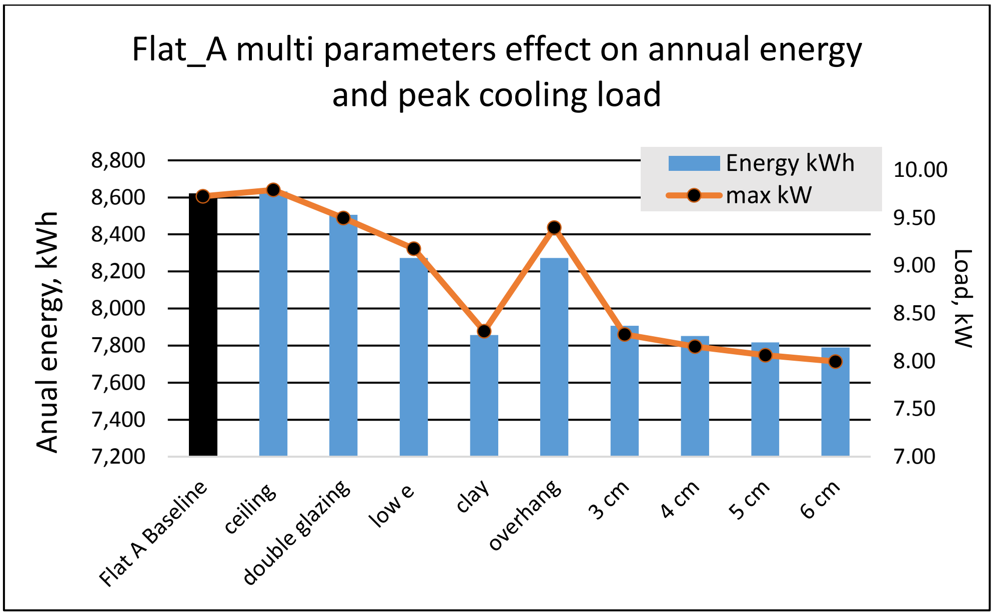


Figure 4-41: Effects of various parameters on Flat A

Simulation results showed that hollow clay blocks again had a positive impact on energy and allowed for a reduction in the cooling load; here, the cooling load was reduced to 8.31 kW and the annual energy consumption to 8,273 kWh, showing 8.3% energy saving compared to the baseline case. Adding an artificial ceiling or suspended ceiling showed absolutely no effect on either load or energy; indeed, the energy consumption was increased, although by only a very small percentage, but this nevertheless showed a negative impact on load with an increase from 9.73 to 9.79 kW, and an increase in energy requirements to 8632 kWh.

The windows to wall surface area ratio were different from one wall section to another, for instance at 8.6% for the bedrooms while the kitchen was the highest at 28.5%, with an average ratio of 13.6% for the entire flat. The effect of changing window glazing was slightly different. By adding double clear glazing, the cooling load decreased to 9.5 kW and energy consumption to 8506 kWh, showing an energy saving of 1.3%. However, adding low emissivity glazing raised the percentage energy saving to 4% and decreased the maximum cooling load to 9.18 kW with an annual energy usage of 8273 kWh. This rate of reduction (4%) was the same as the energy and cooling reduction obtained by adding an overhang external to the windows.

Insulation from 3 to 6 cm thick showed high percentage savings and at different rates. 3 cm thick insulation decreased the energy consumption to 7908 kWh and the maximum load to 8.28 kW, showing an energy saving of 8.3%, while 4 cm insulation slightly increased the saving to 8.9% and reduced the cooling load to 8.15 kW and annual energy to 7852 kWh. With 5 cm insulation, the load was 8.06 kW, and energy was 7817 kWh. However, 6 cm of insulation showed energy savings of 9.6%, and reduce the load to 8 kW and the energy consumption to 7789 kWh. Figure 4-42 shows the effects of all parameters on the peak day in July.

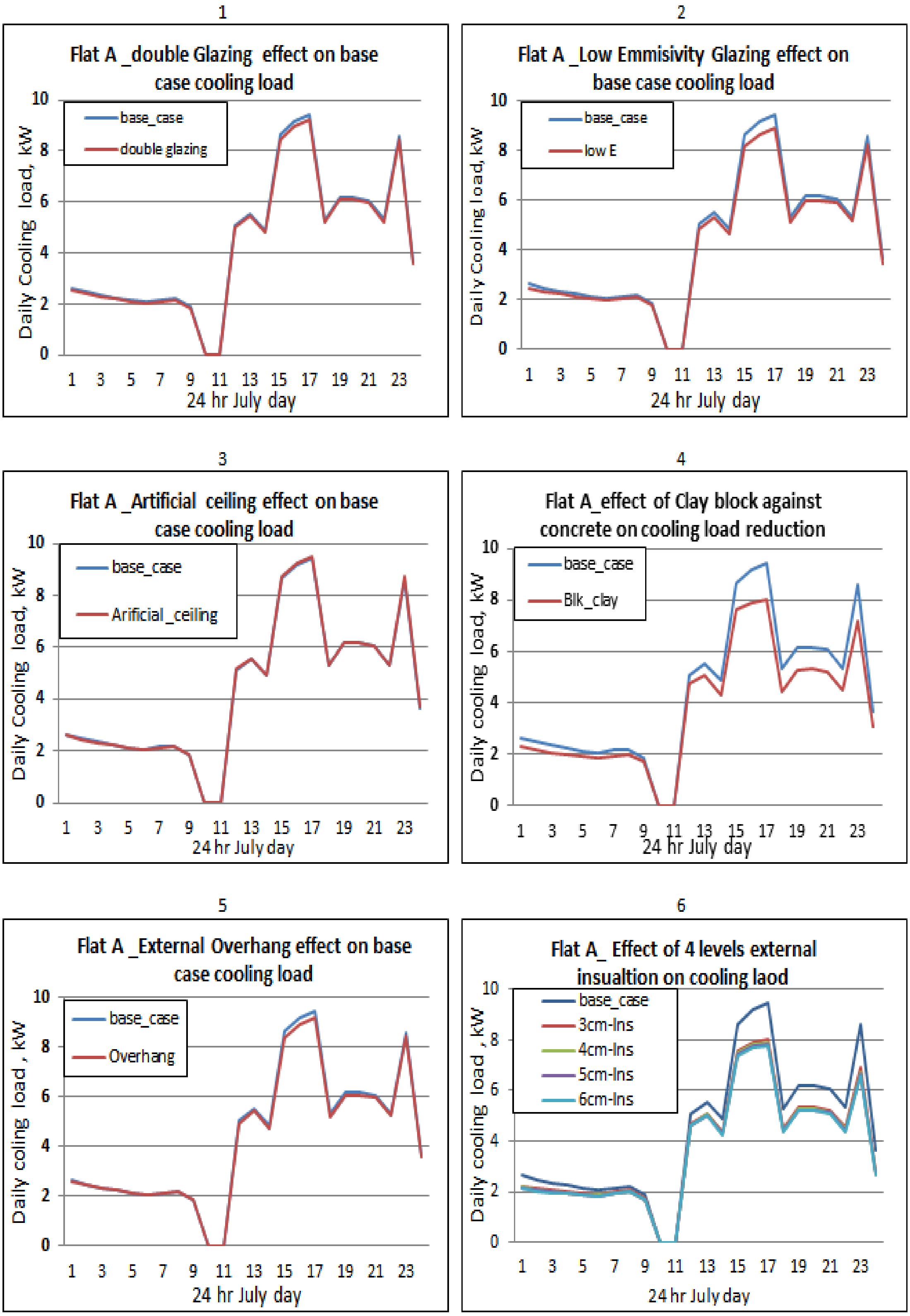


Figure 4-42: Impact of various parameters on cooling load, on the peak day in July for Flat A.

Flat A was investigated in different orientations to predict the optimum orientation, as shown in Figure 4-43. The results showed that the best orientation for Flat A was the North-East orientation because the building has two facades, the baseline module nominally has a South-facing orientation, but in fact, the other part of the building faces the West as well, as per Figure 4-43.

Flat A

0^0	90^0	180^0	270^0
South-West	North-West	North-East	South-East

Figure 4-43: Orientation effect with respect to the baseline position for Flat A

In this orientation, the cooling load recorded was the lowest at 9.07 kW and the annual energy consumption was reduced to 8036.17 kWh, as shown in Figure 4-44, which was then followed by the West-facing orientation (North-West) where the maximum cooling load was reduced to 9.4 kW and the energy consumption to 8272 kWh for the cooling season. The worst orientation for Flat A was the South-East orientation where the cooling load was at its highest of 10.21 kW, and the energy consumption reached 9071 kWh.

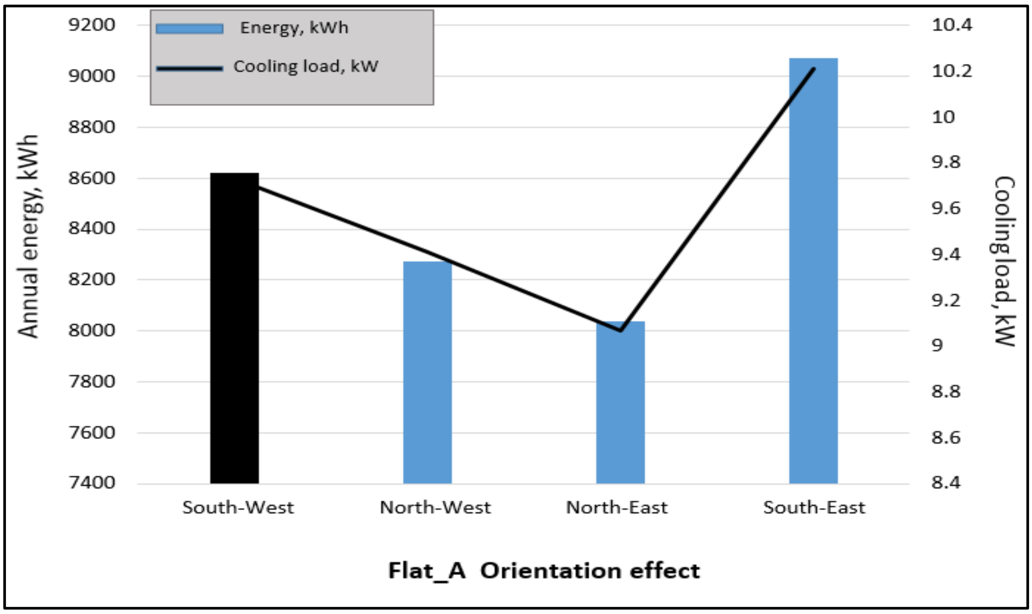


Figure 4-44: Effect of orientation on Flat A energy and cooling load

4.4.3.2 Impact of the Different Parameters on Flat B

The annual energy consumed in Flat B for cooling is 6175.08 kWh and the maximum cooling load is 6.4 kW. The flat was simulated with the various different retrofitting parameters to assess the impact of the associated changes in annual cooling energy and cooling load, as shown in Figure 4-45.

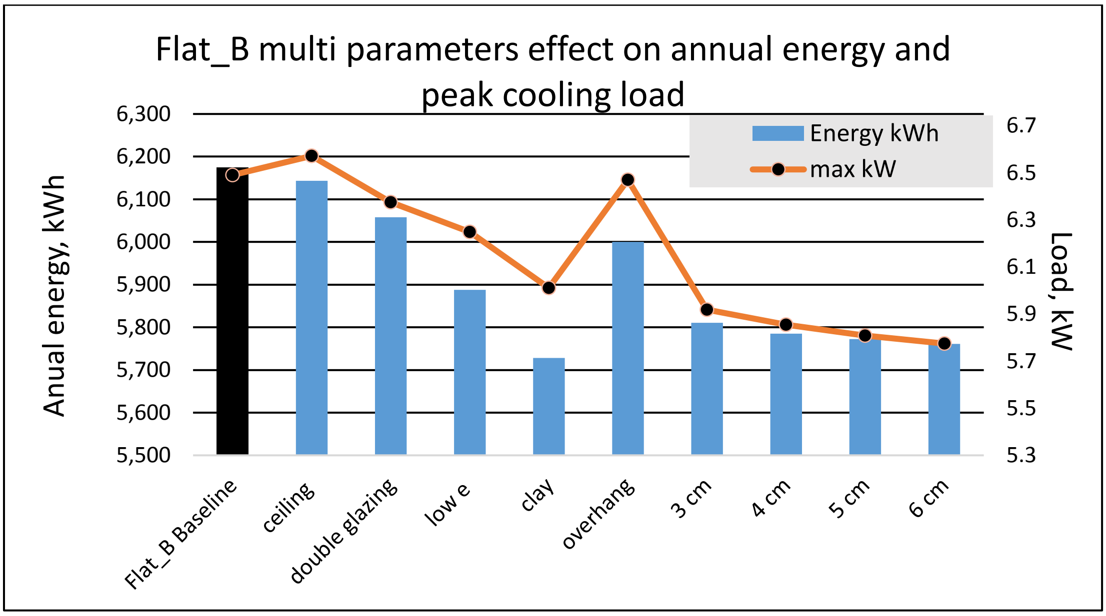


Figure 4-45: Effect of parameters on cooling load and annual energy for Flat B

The suspended ceiling was used to assess its impact on energy saving. In Flat B, the saving that resulted by adding the suspended ceiling in the middle floor again had a negative effect and increased the cooling load to 6.5 kW. However, the energy consumed was slightly reduced as it dropped to 6144 kWh, though this represented only a 0.5% annual energy saving. Double clear glazing and low emissivity glazing were also tested separately. It was noticed that double clear glazing saved only 1.9% more energy with a very little reduction in cooling load, from 6.4 to 6.3 kW, but the low emissivity glazing had slightly more effective, it decreased the cooling load to 6.2 kW and energy to 5888 kWh, recording an annual saving of 4.6%. In this orientation, the overhang was not so effective as it saved only 2.8% annually, reducing the energy to 6000 kWh and with the maximum cooling load remaining the same.

Four different insulation thickness (3, 4, 5 and 6 cm) were applied to Flat B, The results of which showed that adding 3 cm that to the external walls would save 5.9% in energy and reduce the load to 5.9 kW, and that further increases in thicknesses to 4, 5, or 6 cm had only very small effects of about 0.1 kW each difference in cooling load. The associated energy saving was also very small, with saving going from 3 cm to 6 cm equivalent to 5.9 to 6.7%. The more beneficial effect among the various parameters was changing the concrete blocks to clay blocks as the cooling load was accordingly reduced to 6 kW and the annual energy saving to 7.2%. Figure 4-46 shows the impact of each individual parameter on the cooling load during the peak day in July. Two main parameters are the clay blocks insulation and the low emissivity glazing. The most effective parameter is the insulation, whose optimum thickness is 3 cm as this has essentially the same impact as the thicker insulation on the load, though the annual energy is slightly different.

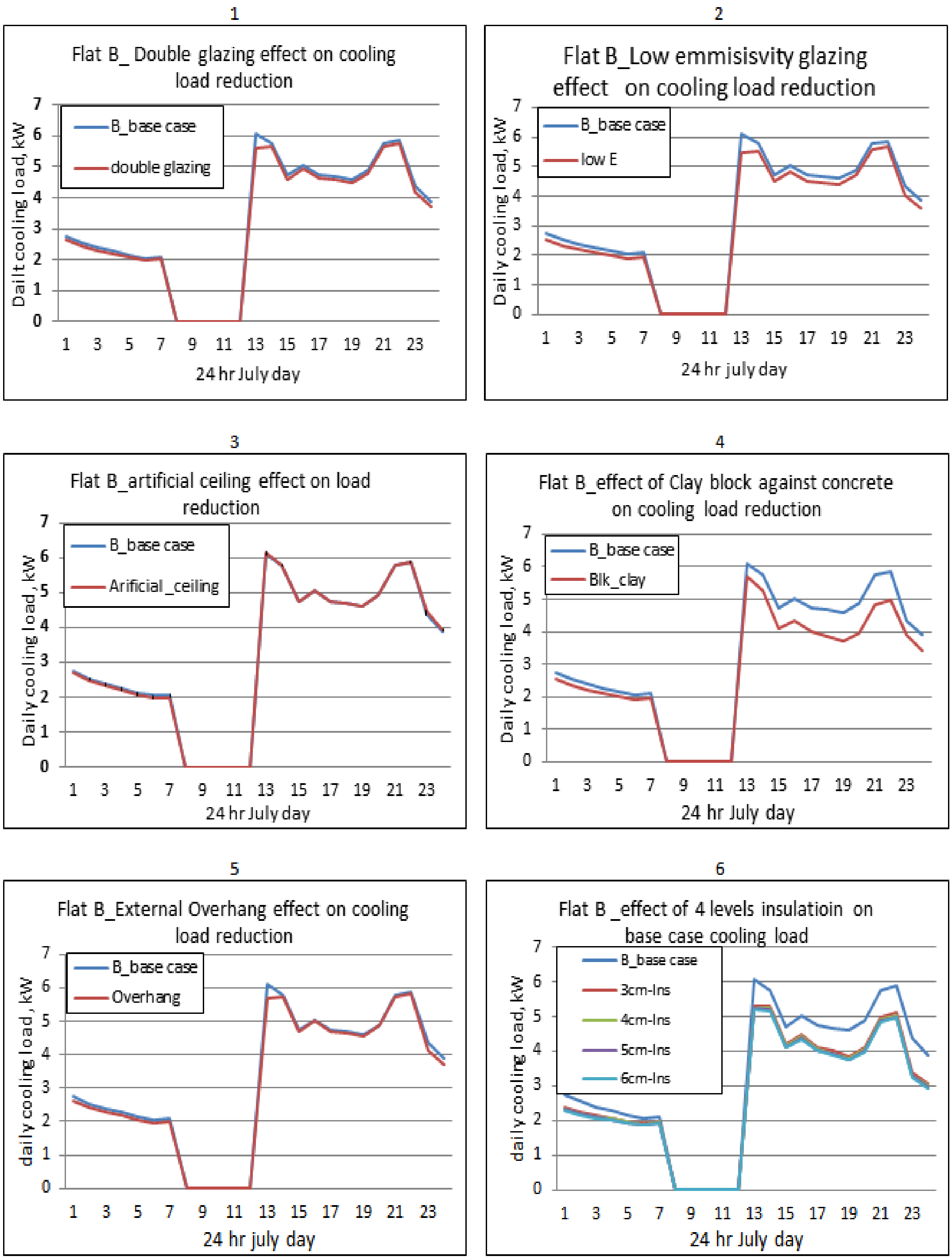


Figure 4-46: Impacts of various parameters on cooling load in July for Flat B

Flat B was simulated with different orientations, as shown in Figure 4-47, with the reference location in the flat block. The results showed that the best orientation is the flat with a 0 degree aspect (North-West facing) in terms of minimum energy consumption and cooling load, as shown in Figure 4-48.

Flat B

0^0	90^0	180^0	270^0
North-West	North-East	South-East	South-West

Figure 4-47: Orientation effect with respect to the baseline position for Flat B

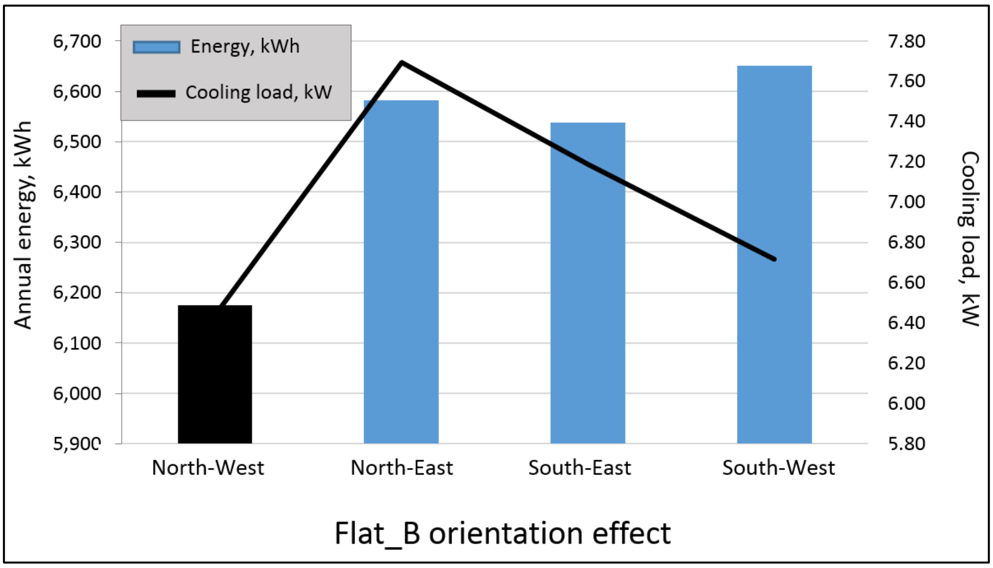


Figure 4-48: Effect of orientation effect on annual energy and cooling load for Flat B

3.5.1.1 Impact of the Different Parameters on Flat C

The annual energy consumption of the baseline module for Flat C was 4188 kWh with a maximum cooling load of 9.6 kW, as shown in Figure 4-49. The suspended ceiling saves only 0.4% of the annual energy consumption and slightly increases the cooling load to 9.8 kW. Adding double clear glazing to the building reduces the maximum cooling load to 9.4 kW and annual energy to 4067 kWh, representing a 2.9% annual energy saving, while for the low emissivity glazing, the cooling load was slightly better than the clear glazing, at 8.9 kW and an annual energy consumption of 3896 kWh, showing a saving of 7% annually at a rate that is more than doubled compared to the savings achieved using clear glazing. When the concrete block was exchanged with the hollow clay block, the cooling load was reduced to 8.9 kW at peak load and the energy consumption reduced to 3609 kWh, representing a saving of 13.8%, which is quite considerable compared to previous parameters. The use of an overhang above the external windows with 13.6% window/wall ratio gives a 4.3% annual energy reduction and reduces the cooling load to 9.4 kW.

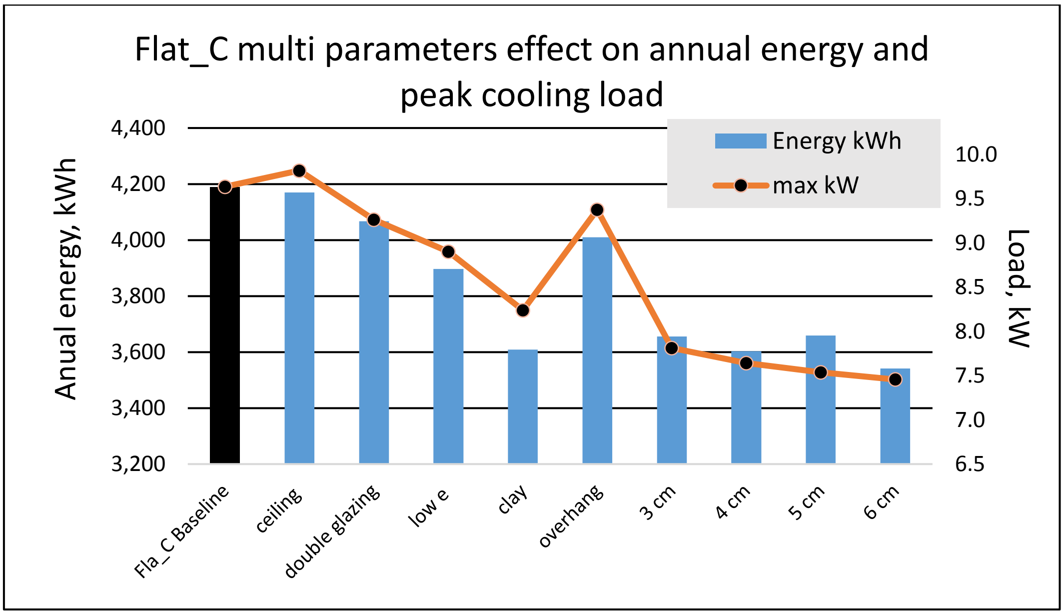


Figure 4-49: The effect of various parameters on cooling load and annual energy for Flat C

It has been shown that 3 cm insulation appears to be the best compromise between thickness and effect, as it reduces the maximum cooling load to 7.8 kW and the energy consumption to 3656 kWh, representing a 12.7% energy saving. The thicker insulations of 4, 5 and 6 cm increase the annual energy saving slightly, as shown in Figure 4-49, but not in a cost-effective manner.

Figure 4-50 shows the hourly effect of the same parameters in mid-July day, illustrating the timing of that effects on cooling load and subsequently affect cooling energy. Clay block and insulation reduce the energy consumption even when there is no solar heat gain, which indicates that these materials are acting as a barrier to the heat resulting from solar irradiation to the building.

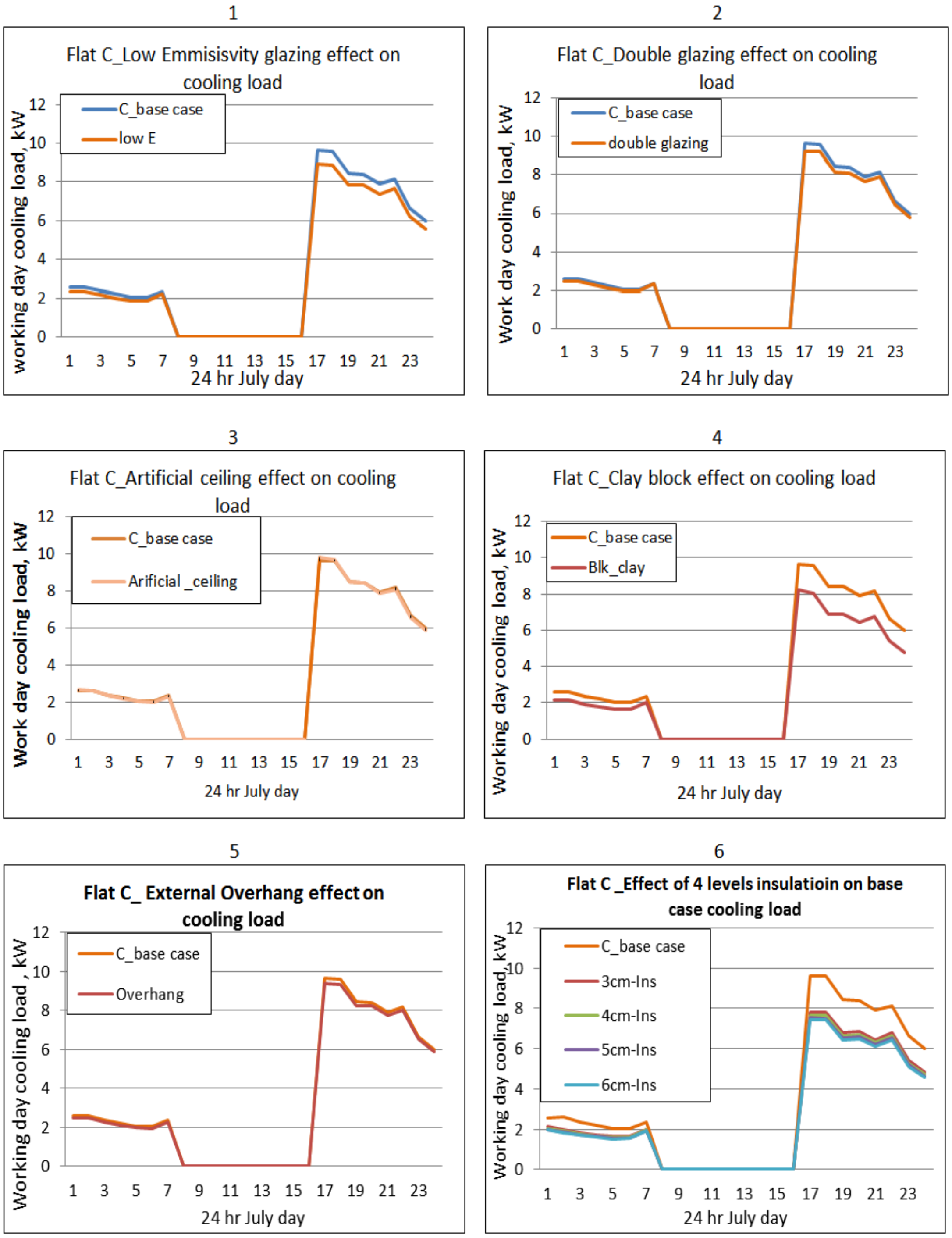


Figure 4-50: Impact of various parameters on cooling load in July for Flat C

Flat C, which is located next to Flat A facing East and South, compared to the Flat A baseline case, and which was then simulated for the other orientations and analysed as shown in Figure 4-51.

Flat C

0^0	90^0	180^0	270^0
South-East	South-West	North-West	North-East

Figure 4-51: Effect of orientation with respect to the baseline position for Flat C

The baseline case which faced South-East should an energy consumption of 4188 kWh for the whole cooling season, with a 9.64 kW peak load. Its original orientation represents the best case, though with other orientations being almost the same, as shown in Figure 4-52.

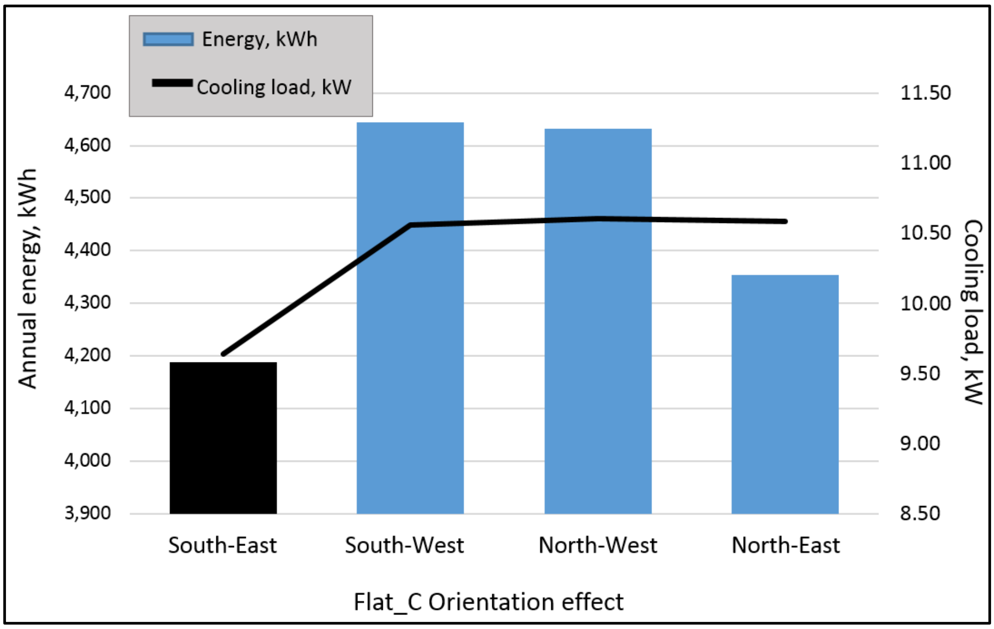


Figure 4-52: Effect of orientation on annual energy and cooling load for Flat C

4.4.3.4 Impacts of the Different Parameters on Flat D

Flat D, which faces North-East, was simulated with the baseline materials and showed a cooling load of 8.6 kW and annual energy consumption of 3050 kWh. It was then simulated with additional retrofitting measures, starting with a suspended ceiling that showed absolutely no effect on the cooling load, as it stayed unchanged, and the energy consumption was only very slightly reduced from 3050 to 3039 kWh. The effectiveness of the suspended ceiling was the same for all flats, which demonstrates that the flats located in the middle story of the building do not benefit from insulating the ceiling in any way. Figure 4-53 shows the impact of all individual parameters on cooling.

Adding the clear double glazing showed a reduction in cooling load to 8.2 kW and energy consumption to 2940 kWh, representing an energy saving of 3.6%. The low emissivity glazing has a greater effect, reducing the maximum cooling to 7.8 kW and energy consumption to 2802 kWh with a saving of 8.1%. Hollow clay blocks were added to replace concrete blocks, showing a reduction of 13.1% in energy and a reduction in the maximum cooling load to 7.3 kW. The overhang has a very good impact on load and energy, showing a 7.3% saving in energy and a maximum cooling load reduced to 8 kW. The insulation has a significant impact on both load and energy, with the four thicknesses of 3, 4, 5, and 6 cm reducing the baseline load from 8.6 kW to 7.2, 7.1, 7, and 6.9 kWh, and energy consumption savings of 9.8, 10.6, 11.1 and 11.5%, respectively. This demonstrates that 3 cm is the most cost-effective insulating if applied to the external layer of the building because increasing the thickness from 3 to 6 cm only reduces the annual consumption by 0.4%, a negligible amount compared to price and thickness of the material.

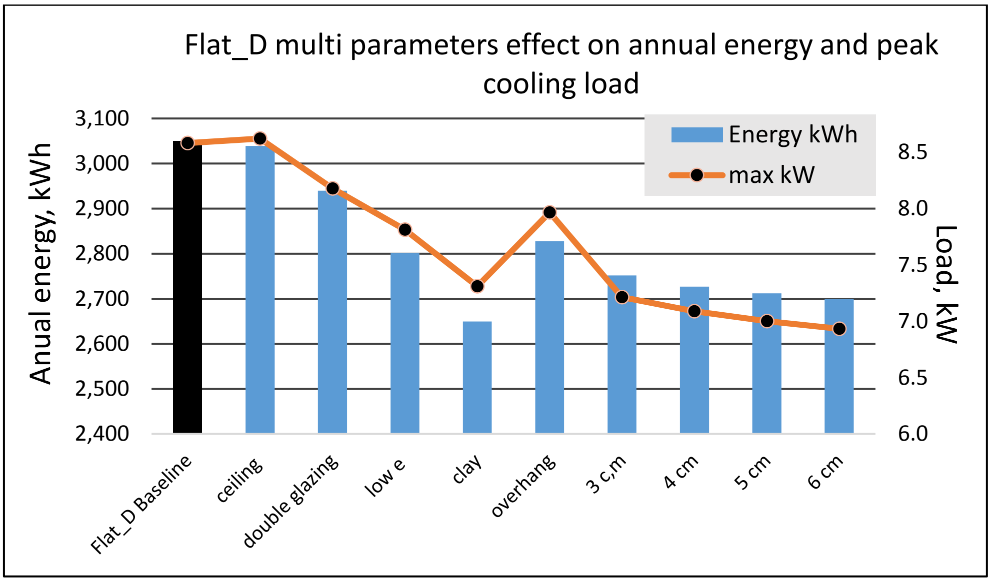


Figure 4-53: Effect of various parameters on cooling load and annual energy for Flat D

Figure 4-54 shows the hourly simulation for Flat D for the peak day in July. This figure illustrates the hourly effect of each parameter over the course of a day, where again clay blocks and insulation are among the most effective modifications as they delay the penetration of heat into the building, whilst all the other parameters have relatively low or negligible impacts.

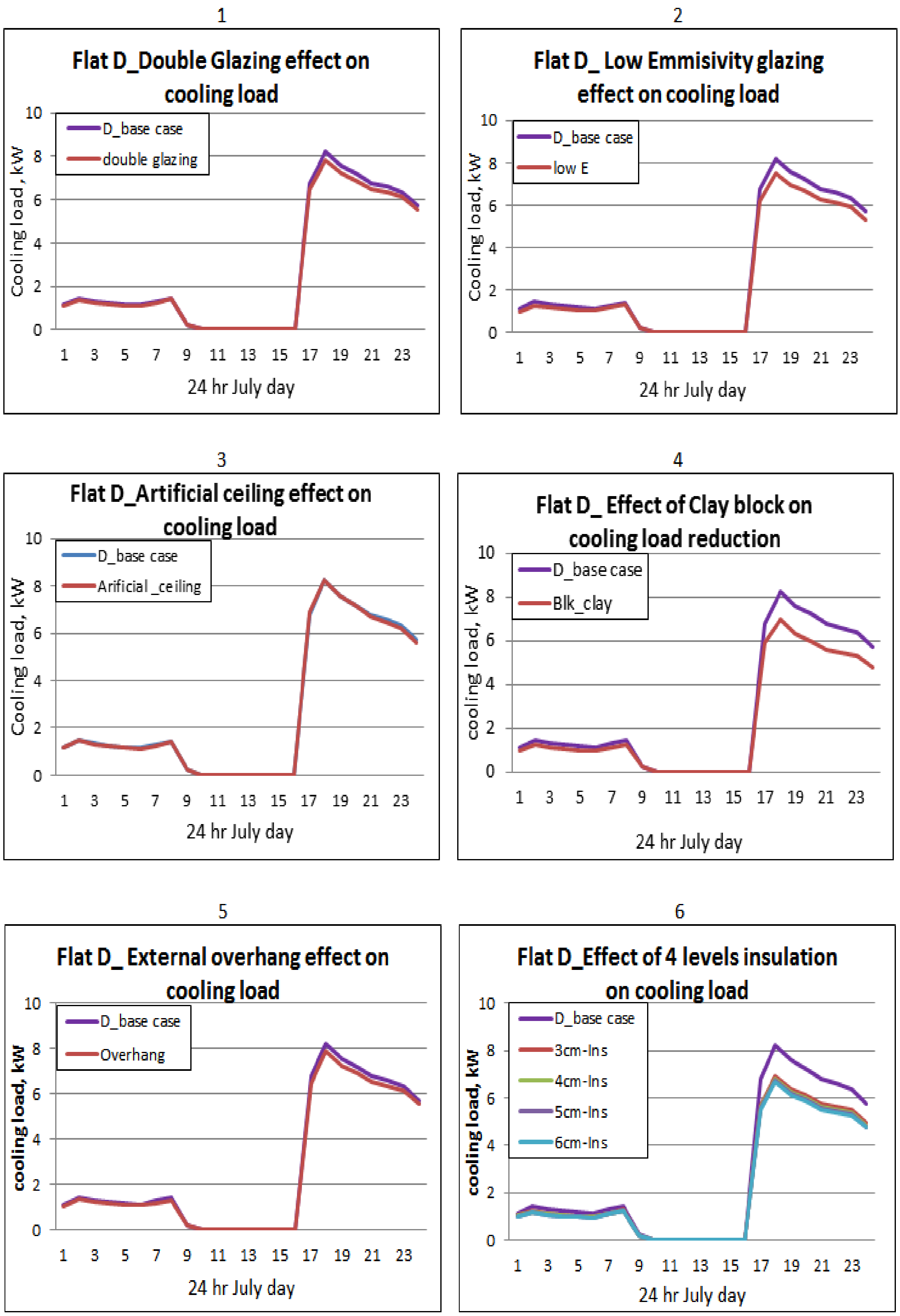


Figure 4-54: Impacts of various parameters on cooling load in July for Flat D

This flat was separately examined for the effect of orientation on its cooling load, and energy consumption, as shown in Figure 4-55 .

Flat D

0^0	90^0	180^0	270^0
North-East	South-East	South-West	North-West

Figure 4-55: Orientation effect with respect to the baseline position for Flat D

The baseline orientation for Flat D is North-East, in which the consumption is 3050 kWh and the maximum load is 8.6 kW. The South-West orientation is the optimum for this flat, as this orientation shows the minimum load and energy in Figure 4-56. The worst orientation is South-East when the cooling load reaches 9.6 kW and the energy consumption rises to 3255 kWh. It should be noted that this flat consumes less energy compared to others as the cooling is off for two days and is unoccupied for long periods.

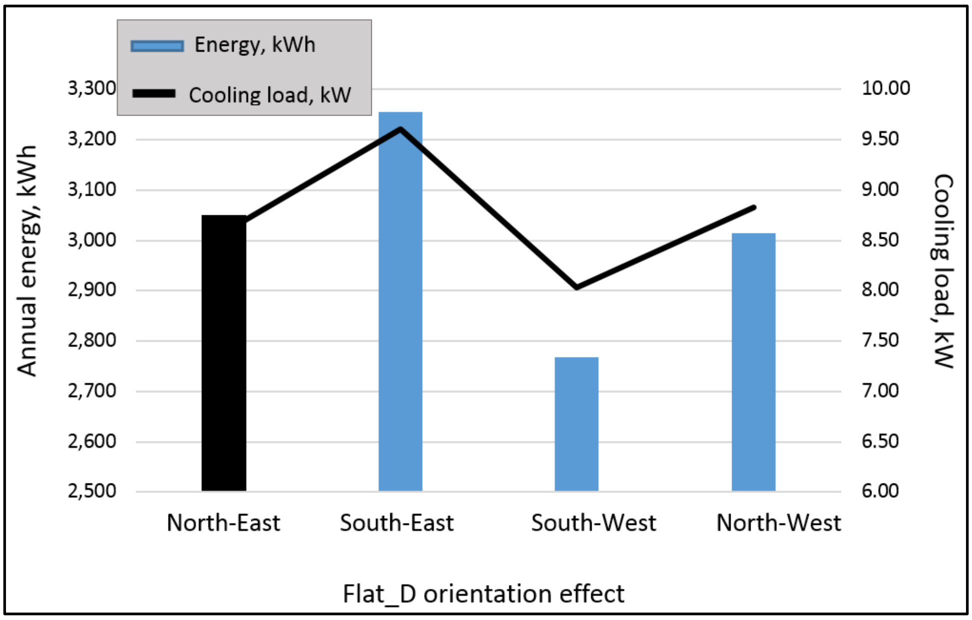


Figure 4-56: Effect of orientation on annual energy and cooling load for Flat D

4.4.3.5 Impact of the Different Parameters on the Combined Flats

Following the separate simulations of the four flats, the combined flats, or the consumption of all four flats together (combined flats) was analysed to assess the effects of the various parameters. Figure 4-57 shows the 1st floor flats' energy and cooling loads, following the application of the parameters mentioned earlier. From this, is was concluded that the suspended ceiling has a very small impact on cooling load reduction or energy-saving, as its annual energy saving is 0.22%, or in other words, negligible. Double glazing saves 2.1% of the annual energy consumption, but low emissivity glazing is slightly better as it recorded a saving of 5.33%. Clay blocks have an excellent impact in that it reduces the load from 30.87 to 26.38 kW and results in a 9.94% saving in annual energy consumption. Adding an external overhang is beneficial, though not very much, so as the associated energy saving is only around 4.19% because of the low windows/wall surface area ratio of 13.6%; the availability of internal shading, however, has a very big impact on the cooling load and energy consumption.

Insulation has a clear impact on the load and energy, where adding external insulation around the building to a 3 cm thickness lowers the load from 30.87 to 25.89 kW and decreases the energy consumption from 22,033 to 20,125 kWh. This represents 8.66% saving, whilst a 4 cm thickness reduces the cooling load to 25.48 kW and energy saving by 9.38%, and a 5 cm thickness reduces the cooling load very slightly to 25.1 kW and energy saving by 9.82%. Finally, the 6 cm thick insulation reduces the total cooling load to 24.96 kW and energy consumption to 19791.9 kWh, showing the maximum energy saving of 10.17%. The optimum insulation thickness for the entire combined flats building is thus 4 cm.

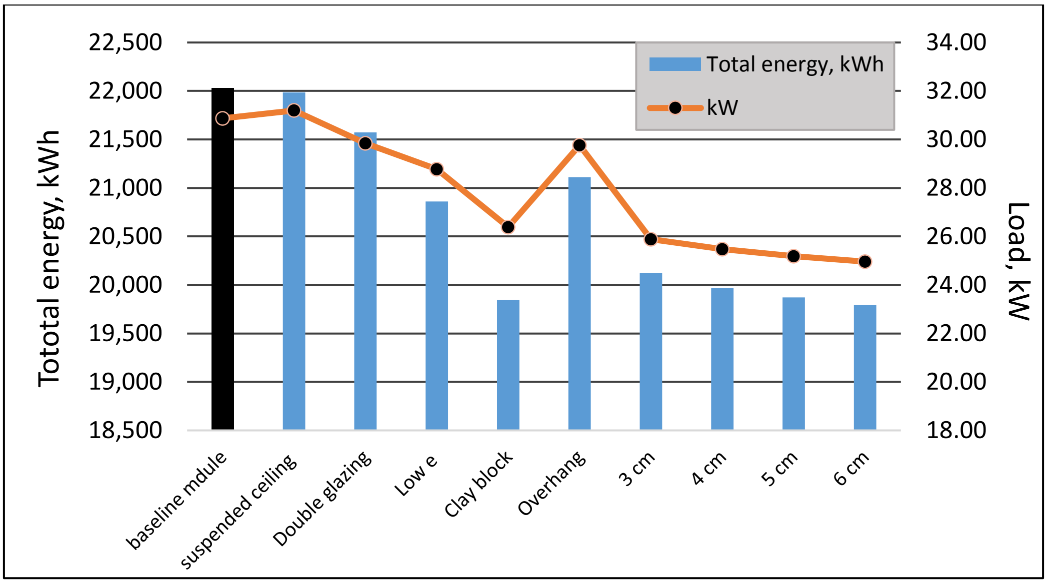


Figure 4-57: Impact of various parameters on cooling load and annual energy for the combined flats

Figure 4-58 shows the parameters' effects on the first-floor buildings, which represents the combined flats on the peak day in July. The effects of clay blocks and insulation are entirely obvious, while the effects of suspended ceiling, overhang and double-glazing are negligible.

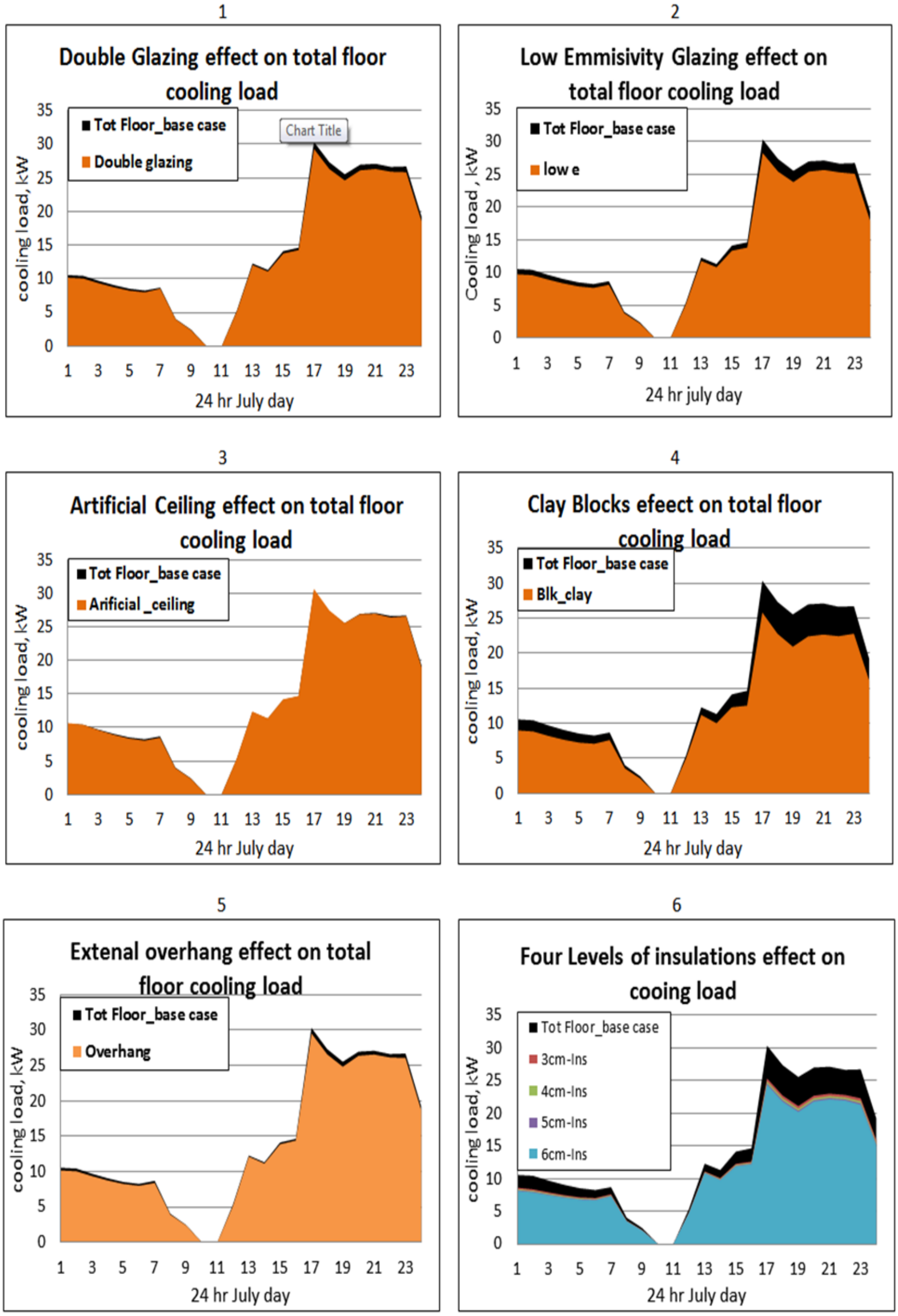


Figure 4-58: Impact of parameters on the total cooling load.

The impact of the orientations on cooling energy and cooling load for the combined flats was simulated, the results of which showed that the North orientation was optimal, as shown in Figure 4-59, and that the worst orientation was East-facing. This analysis only holds, however, if the flats use their cooling systems according to the schedules set for them; if the schedule changes, clearly the whole analysis can change with it.

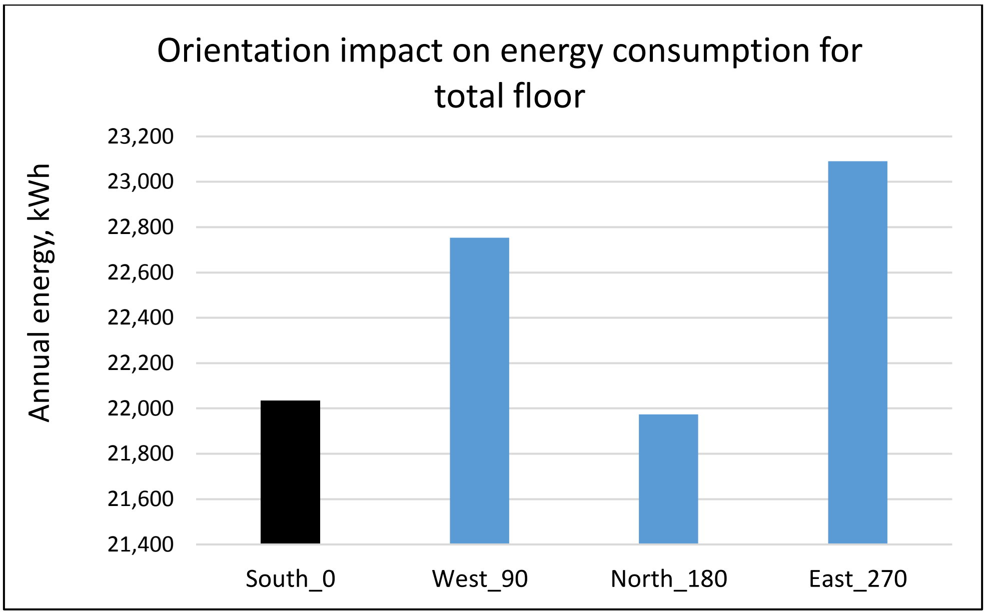


Figure 4-59 Impact of orientation on combined flats' cooling energy consumption

Generally, each case needs to be examined separately to find the optimal orientation, as there are multiple parameters play role in estimating the cooling load and energy. The simulation results have shown the best orientations for each of the four flats and as combined flats. If it is generalised to assess the whole building, the North then South orientation are the best according to the cooling load and energy consumption. Consequently, it helps designers and constructors to amend their designs for further energy saving, as the East and West orientations need to be improved for the mentioned purpose.

4.5 Cooling Load Ranges of the Flats

Each flat unit from the building was simulated for six months from April to September, i.e., the cooling season, and covers a total of 4392 hours. EnergyPlus was used for the simulations using Erbil city weather files. These simulations resulted in a large number of cooling load profiles representing the cases of each unit studied on an hourly basis.

Table 4-12 represents the range of cooling loads in each baseline flat. The maximum load for each flat is different. Flat A has only 18 hours out of 4392 hours that need loads over 9 kW, representing only 0.4% of the seasonal cooling hours, and 64 hours of loads between 8-9 kW, which represents 1.5 % of the simulated hours.

For Flat B, the maximum cooling load is between 5-6 kW which occurs for 124 hours or 2.8% in total, whilst a lower load of 4-5 kW covers 7.8 % of the simulated hours. Flat C has a high load because of its location within the building, although the maximum load is over 9 kW only for 5 hours, representing 0.1%, need a 9 kW cooling load. The cooling range from 8-9 kW represents 0.4% of the total simulation hours (16 hours), whilst the range for Flat C slightly higher and goes up to 1.2 % (85 hours) of 7-8 kW load. The maximum load for Flat D is between 8-9 kW, which occurs for only 3 hours per year, followed by 18 hrs of 7-8 kW and then 73 hours of 6-7 kW cooling load.

Table 4-12: Baseline cooling load ranges for the studied flats

Load range of base case, kW	Flat A hours	A %	Flat B hours	B %	Flat C hours	C %	Flat D hours	D %
0-2 kW	2330	53.1	2648	60.3	3512	80.0	3665	83.4
2-3	604	13.8	740	16.8	142	3.2	117	2.7
3-4	405	9.2	530	12.1	159	3.6	154	3.5
4-5	422	9.6	341	7.8	178	4.1	206	4.7
5-6	306	7.0	124	2.8	151	3.4	156	3.6
6-7	136	3.1	9	0.2	149	3.4	73	1.7
7-8	107	2.4	0	0.0	85	1.9	18	0.4
8-9	64	1.5	0	0.0	16	0.4	3	0.1
9- OVER	18	0.4	0	0.0	5	0.1	0	0.0
Total hours	4392		4392		4392		4392	

4.6 Operational Set Temperature Effect

The comfort set temperature, as based on ASHRAE, is between 24-28^{o}C over the summer season for hot environments depending on design [59]. However, increasing the internal cooling set temperature might not be a desirable strategy, but it is very effective and saves a lot of energy. In the case of a residential building when the metabolic rates of the occupants are low, and the human body is not producing too much heat, then people can adapt to a slightly higher temperature, this consequently reduces cooling load. Table 4-13 shows the effects of increasing the internal set operative temperatures on energy consumption and the maximum cooling load for all four flats. This method helps to assess peak loads as they fluctuate because of the external weather conditions. Raising the internal set temperature by one degree would reduce the load in flat A by 5.5% and for the other flats over a range between 7.3-8.3%, and the comfort level would still be intact if this approach were followed.

Table 4-13: Impact of temperature increase on load and energy

Set Air Temperature	Flat A Load, kW	**Flat B** **Load, kW**	**Flat C** **Load, kW**	**Flat D** **Load, kW**
25 ^{0}C	9.7	6.4	9.6	8.6
26 ^{0}C	9.2	5.9	8.9	7.9
27 ^{0}C	8.7	5.6	8.3	7.3
28 ^{0}C	8.1	5.6	7.6	6.7
29 ^{0}C	7.6	5.3	7.0	6.1
Energy at temperature	Flat A kWh	Flat B kWh	Flat C kWh	Flat D kWh
Energy 25^{0}C	8620.5	6175.1	4188.1	3050.2
Energy 26^{0}C	7804.1	5543.5	3705.6	2729.5
Energy 27^{0}C	6987.6	4928.8	3239.6	2418.1
Energy 28^{0}C	6181,0	4317.7	2785.6	2116.6
Energy 29^{0}C	5403.1	3725.3	2351.9	1825.8

4.6.1 Hot Months' Average Load Peaks Calculation

The cooling load of all the buildings is based on the set of calculations from the EnergyPlus simulation software; data are taken from the weather file representing the case of the location being studied [165]. By keeping the internal heat gain unchanged due to the occupants, lighting and equipment (which is not unreasonable as an assumption), the sole load pattern that could then change would be from the effect of external parameters, where solar irradiation and high variable temperatures would change the pattern and outline of the cooling load profiles regardless of the internal parameters, as the inputs kept constant for this study period and depend on the set of schedules for each building. To assess the pattern of each building's peak loads, two hot months in summer conditions were used, July and August, where daily peak load values were used to determine the load averages for each building. This was repeated for all building units to decide the best load for the design. This is a very useful method by which to reduce the size of a cooling unit while maintaining the comfort level, or knowing what level the internal temperature will rise to.

4.6.2 Flats Average Peak Load

The daily peak loads for all four baselines for Flats A, B, C and D and the parameters studied were selected over July and August, covering 62 days in total. The selected loads were then averaged to analyse and design the optimal size of the cooling system to provide adequate cooling and preventing comfort levels being exceeded. Using such a strategy results in some unmet set temperature hours but saves energy.

Table 4-14 shows the maximum cooling loads with the effect of each parameter for each separate flat and the combined flats. The second part of the table is the averaged peaks for July-August for each flat. The cooling load of Flat A reduces to 7.88 kW with the effects of these parameters; Flat B’s cooling load reduced to 5.09 kW, Flat C to 6.39 kW and Flat D to 5.39 kW.

Table 4-14: Maximum load and maximum average with parameter effects

Maximum and averaged peak loads for each flat with each selected parameter											
		baseline case	ceiling	double glazing	low E glazing	clay block	overhang	3 cm	4 cm	5 cm	6 cm
Max load (kW)	max A	9.73	9.79	9.50	9.18	8.31	9.40	8.28	8.15	8.06	8.00
	max B	6.44	6.52	6.32	6.20	5.96	6.42	5.87	5.80	5.76	5.72
	max C	9.64	9.82	9.26	8.90	8.24	9.38	7.81	7.64	7.54	7.46
	max D	8.58	8.62	8.18	7.81	7.31	7.97	7.21	7.09	7.00	6.93
	max total	30.87	31.20	29.84	28.77	26.38	29.77	25.89	25.48	25.18	24.96
average of peak (kW)	Flat, kW	base case	ceiling	double glazing	low e	clay	overhang	3 cm	4 cm	5 cm	6 cm
	A	7.88	7.93	7.72	7.45	6.81	7.65	6.85	6.77	6.71	6.67
	B	5.09	5.10	5.02	4.93	4.69	5.05	4.71	4.67	4.64	4.62
	C	6.39	6.45	6.18	5.95	5.50	6.22	5.41	5.32	5.26	5.21
	D	5.39	5.43	5.17	4.95	4.66	5.08	4.69	4.63	4.59	4.56
	Total	21.15	21.34	20.55	19.82	18.29	20.48	18.25	18.02	17.85	17.72

Figure 4-60 shows the daily peak from July-August and some unmet hours. Table 4-12 shows the numbers and ranges of the loads for each flat. For Flat A, loads over 8 kW reach 82 hours in total. This load is based on a 25°C operational temperature. Using the method of peak averaged load, the unmet hours will have a range of temperatures from 26-29°C, as shown in Table 4-13.

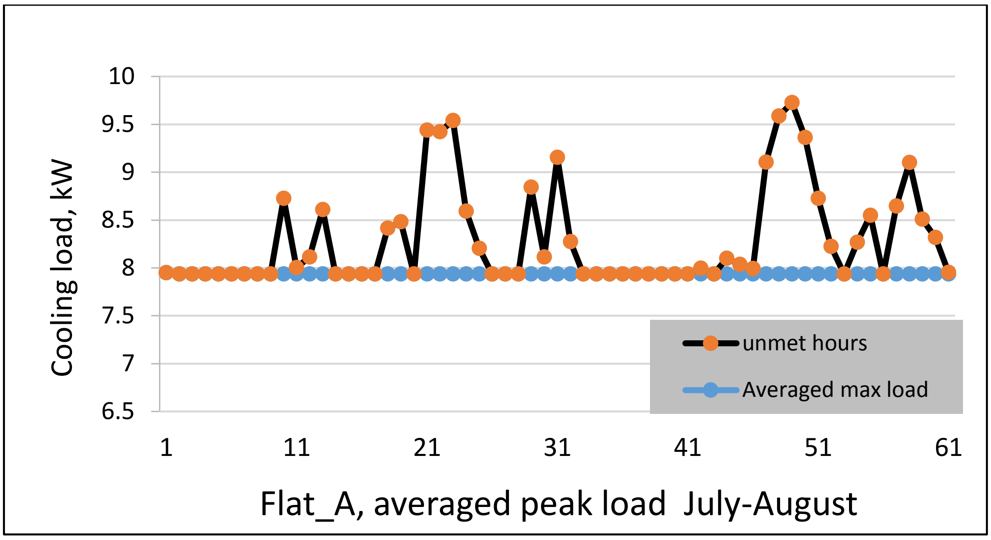


Figure 4-60: Averaged load and unmet hours in July-August for Flat A

Figure 4-61 shows the unmet hours from July-August for Flat B. The averaged maximum cooling load for Flat B is approximately 5.1 kW. The number of hours that cross this load value is shown in Table 4-12, which amounts to 133 hours. The set temperatures and the associated cooling loads for Flat B are illustrated in Table 4-13. Loads between 5.5-5.9 kW result in an operative temperature of 26-27°C, and from 5.6-5.2 kW results in 28-29°C.

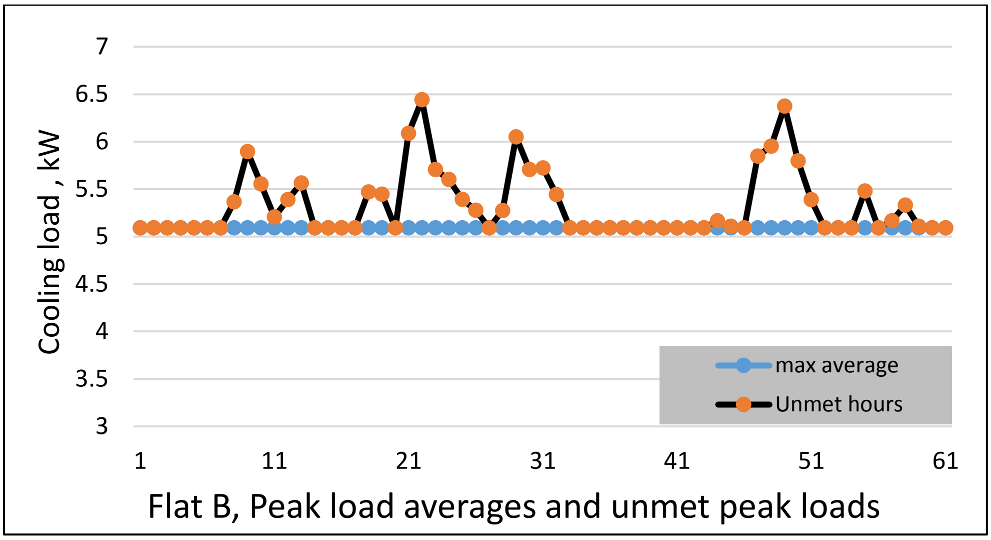


Figure 4-61: Averaged load and unmet hours in July-August for Flat B

Figure 4-62 shows the averaged peak load and the unmet load exceeding the average by almost 2 kW for a few days, where the average load was set to be 7.35 kW for the baseline case. Table 4-12 shows the cooling load hours for Flat C. A design load of 7.35 kW cannot cover about 100 hours, a small portion of load for five hours exceeding 9 kW, representing 0.1% of the total hours. The design cooling load between 7-8 kW for Flat C results in a 28 °C operative temperature, and the loads between 8.9-8.2 kW result in 26-27°C, as shown in Table 4-13.

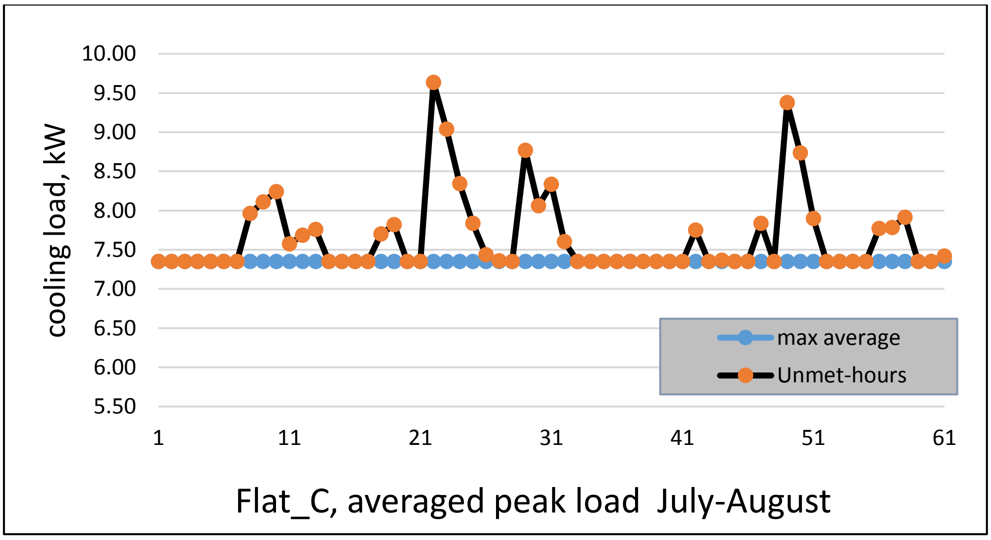


Figure 4-62: Averaged load and unmet hours in July-August for Flat C

Figure 4-63 shows the unmet hours in July-August for Flat D. The averaged peak cooling load for Flat D is approximately 5.39 kW. A total of 143 hours are not covered by this load, though Table 4-12 shows the load between 5-6 kW to be 156 hours, but on further analysis of the baseline loads from that range, loads falling under 5.39 kW total 143 hours. It may be noted from Table 4-13 that the energy consumption is relatively low in Flat D because the operating times and the scheduling of the occupancy (on Thursday-Friday the cooling is off). The load is still as high as high 8.6 kW, where lowering this load to be covered by a system with 5.39 kW would raise the internal temperature during some hours to over 30°C. Any cooling load lower than 6.1 kW for will result in an increase in internal temperature to 29℃ that will result in discomfort, even with the availability of the cooling system. Hence, this method of average peak load for this flat is not very effective and requires a trade-off between the internal temperatures and the load ranges in order to make a decision in this regard. This is regardless of the number of days that the occupants use the building, as the scheduling only effects the energy consumption.

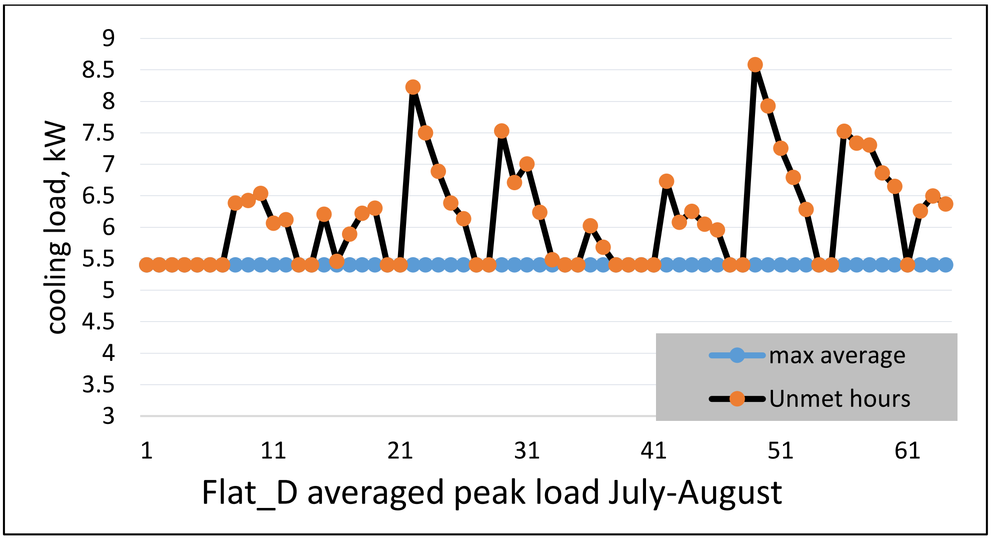


Figure 4-63: Averaged load and unmet hours in July-August for Flat D

The combined flats peak load was averaged from July until the end of August in the same manner as the four individual flats. Figure 4-64 illustrates the cooling loads that exceed the averaged cooling load; in this hourly simulation, Flat C and Flat D affect the value of these peaks. By following the same strategy as for the daily peak average, the average for the combined flats will decline to the lower value of 21.15 kW, where in this calculation we anticipate the effect of individual flat behaviour on the total capacity. Figure 4-66 shows the number of unmet hours over 21.15 kW for the combined cooling of the flats.

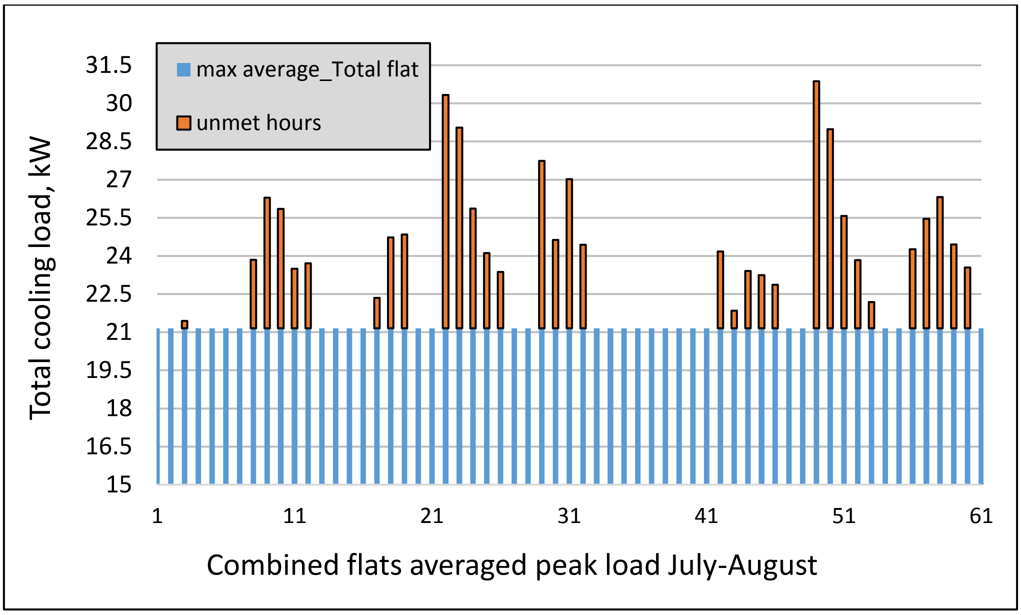


Figure 4-64: The combined flats' averaged load and unmet hours in July-August

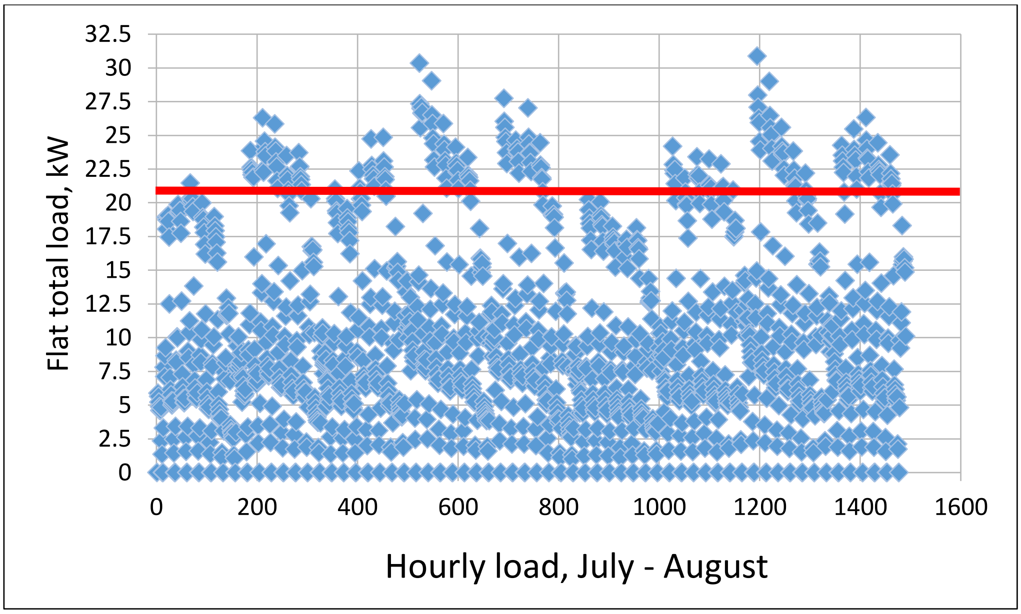


Figure 4-65: Combined floor peaks averaged cooling load

Although the unmet hours are just under 200 hours, the magnitude of unmet the load is significant, and there is quite a large gap between the average and the daily peaks of the month. As it is not known which zone will be affected in case it designed in this way. Another method of weekly average was used, the method is calculating the averaged peak of each summer week starting from July till the end of August. The associated value was found to be 26.77 kW, which means raising the average to 5.6 kW would cover the unmet hours and reduce the large gap between the peaks. This strategy would cover almost all hours apart from the 7 hours over 26.77 kW, and the internal temperature could get as high as 29°C when the building is designed with a 26.77 kW cooling load. Table 4-13 shows the loads as well as the internal temperature. In this method of averaging the peak cooling load, the decision must be taken with considering the load value and the internal temperature rise to avoid the discomfort in the zones.

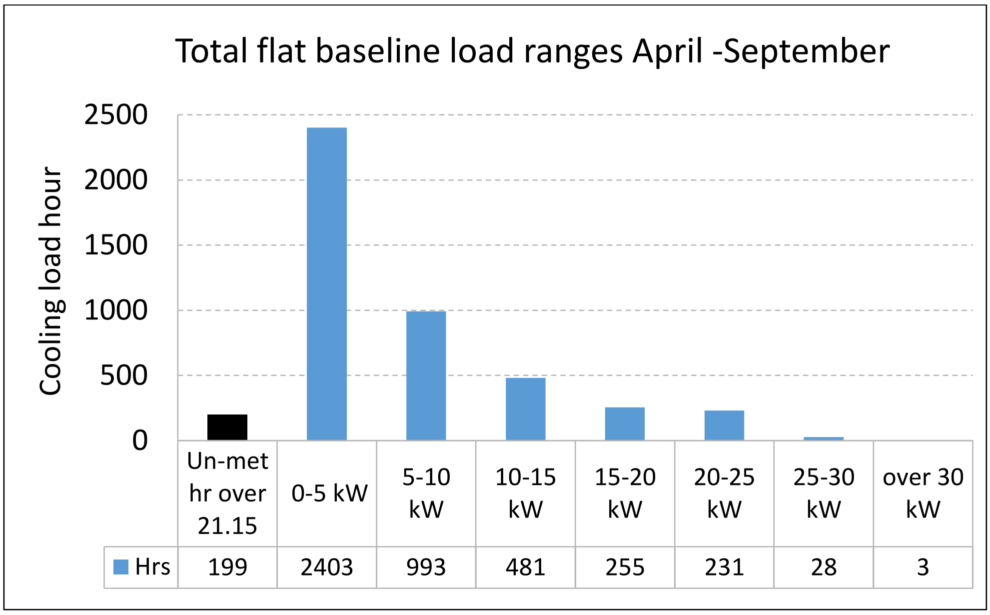


Figure 4-66: Baseline combined flats' cooling load ranges

4.7 Combined Effects of Parameters

The combined effects of the various parameters were evaluated using the exact same procedure used in case study 1 in 4.2.6.2, and the parameters illustrated in Figure 4-67**.**

4.7.1 Effects of Multiple Parameters on Flat A

The building was simulated again to find the optimum combination of parameters that showed the lowest energy consumption. It was predicted that, as parameters, the hollow clay brick, 6 cm insulation adding, low emissivity glazing and overhang, without the suspended ceiling and with the original South-West orientation gives the best outputs would most affect the outcome. It was shown that the peak load could be significantly reduced from 9.7 kW to 7.1 kW, as shown in Figure 4-67**.** The annual energy consumption is accordingly reduced to 7033 kWh, representing a 14.85% saving, by reducing the insulation to either 5 cm or 4 cm, representing annual reductions to 7047 and 7065 kWh that represent 14.7% and 14.5%, respectively, whilst the 3 cm thick insulation reduces consumption to 7095 kWh, itself representing a saving of 14.14% on annual energy consumption. Hence, as the difference due to doubling the insulation was negligible, 3 cm thick insulation would be optimum if the cost is taken into consideration. All the previously mentioned combinations do not include the suspended ceiling, as it has found that this had no associated energy saving.

In the instance of using insulation over hollow concrete blocks, the best combination is concrete blocks, 6 cm insulation, low emissivity glazing and overhang, and no suspended ceiling, which reduced the energy consumption to 7164 kWh representing a saving of 13.3%. Reducing the insulation thickness to 3 cm with the same other parameters would save 11.9% annually, with an associated energy consumption of 7274 kWh. Increasing the thickness to 4 cm would save 12.5% annually, and as this is only a 48 kWh absolute difference annually, a 3 cm thickness was considered optimum. Increasing insulation from 3 to 6 cm will save only 62 kWh annually, which is again negligible and clearly not cost effective.

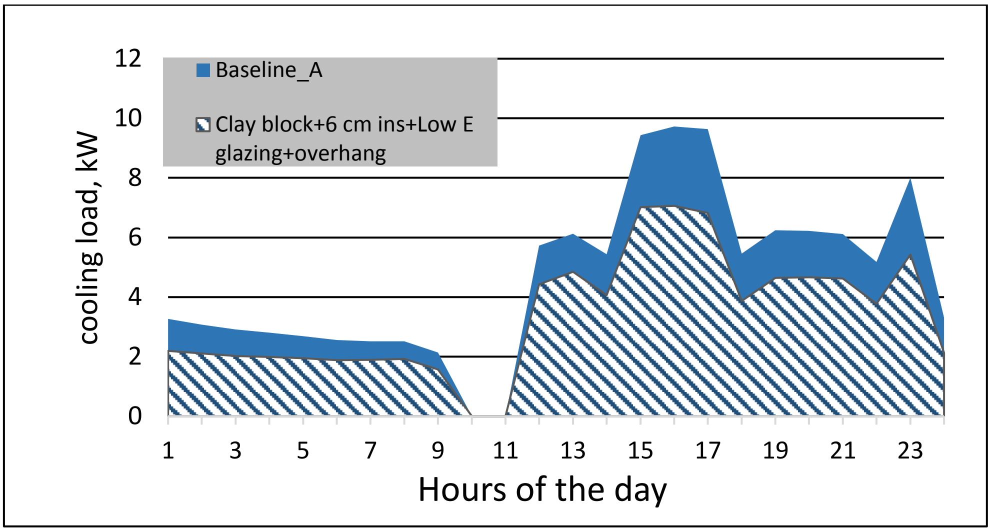


Figure 4-67: Maximum effect of multiple parameters on Flat A cooling load

The North-East orientation shows the lowest energy consumption for Flat A. The same combination of parameters as previous reduces the annual energy consumption to 6801kWh, while the combination with suspended ceiling would actually *increases* the energy consumption slightly. Finally, reducing the insulation from 6 to 3 cm would result in a slight increase in the energy consumption of 56 kWh per annum.

4.7.2 Effects of Multiple Parameters on Flat B

The same method of multiple parameters was applied to Flat B, this is to find the effects of the combination of parameters on the energy and cooling load. The optimum combination of hollow clay bricks, 6 cm insulation on the external wall, low emissivity glazing, with overhang and no suspended ceiling as parameters was investigated. The suspended ceiling was found to have a negative effect because of the flat benefits from the above ceiling for cooling. The energy-saving was found to be 12.2%, and the total energy consumption was reduced from 6175 to 5147 kWh; maintaining all other parameters but reducing the thickness of the insulation to half (3 cm only), the energy consumption increases slightly to 5175 kWh showing 11.7% energy saving, or a difference of just 27 kWh. This demonstrates that the 3 cm is the optimum thickness. The maximum load for Flat B will be reduced from 6.4 to 5.14 kW. When the thickness of the insulation is reduced from 6 cm to 5 cm, the annual energy saving decreases very slightly, giving 12.1% instead of 12.2% which is essentially negligible. The combination of concrete block, 6 cm insulation, low emissivity glazing, overhang and no suspended ceiling as parameters was found to produce a saving of 10.47%, which is almost identical to the combination of clay block, 3 cm insulation, low E glazing, overhang and suspended ceiling, which gave a 10.26% saving in energy.

This is an indication that the addition of an extra 3 cm of insulation with concrete blocks would be equivalent to the use of clay blocks if it is used in the building construction. Figure 4-68 illustrates the combined effects of the parameters on Flat B compared to the baseline module for one day.

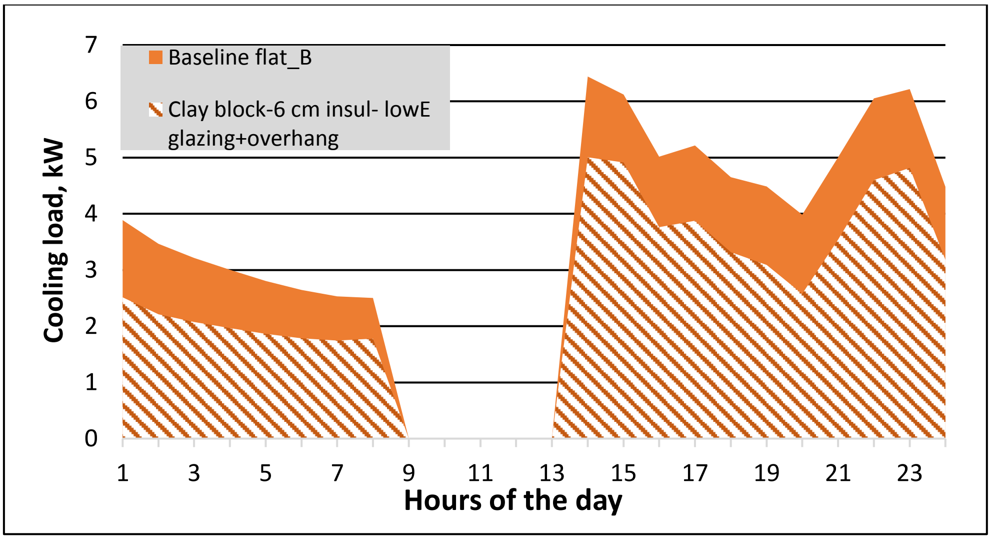


Figure 4-68: Maximum effect of multiple parameters on Flat B

The best orientation for Flat B was the North-West baseline orientation with the above combination. The second-best orientation is the South-East orientation with the combination of clay blocks, 6 cm insulation, low emissivity glazing, overhangs and suspended ceiling as added parameters. These two orientations show annual energy consumptions of 5333 kWh and 5347 kWh, respectively; although the difference is very small, nevertheless orientation has an impact as a parameter, this is shown earlier in Figure 4-45

4.7.3 Effects of Multiple Parameters on Flat C

The combination of clay block, 6 cm insulation, low emissivity glazing with overhang and no suspended ceiling as parameters represents the greatest saving for this flat, with its South-East orientation, showing a high annual energy saving of 31.49% compared to baseline, and a maximum cooling load that is reduced from 9.63 to 5.45 kW. This is a large saving in peak daily load. The same combination with 3 cm insulation, no overhangs and with the suspended ceilings is the optimum, showing an energy saving of 29.79% and reducing the energy consumption from 4188 to 2940 kWh. Adding the overhang to this combination actually reduced the saving significantly to only 25.4%, whilst the difference between 3 cm and 6 cm of insulation was only 71 kWh. The last combination, with or without suspended ceiling, is only a negligible difference. So, 3 cm insulation is the optimum thickness, with any further insulation becoming a waste of money and one which increases the bulkiness of the building. Adding or changing the low emissivity glazing to double clear glazing reduces the saving from 26.8% to 24.8% (3150 kWh), so for this flat the combination of concrete blocks, 6 cm insulation, low emissivity glazing with overhang, and no suspended ceiling is essentially equivalent to the combination of clay block, 4 cm insulation, and no overhang, where for this combination a 2 cm insulation thickness with the external overhang is equivalent to changing the concrete to clay block. Figure 4-69 shows the greatest reduction in cooling load with all parameters optimised but without the suspended ceiling.

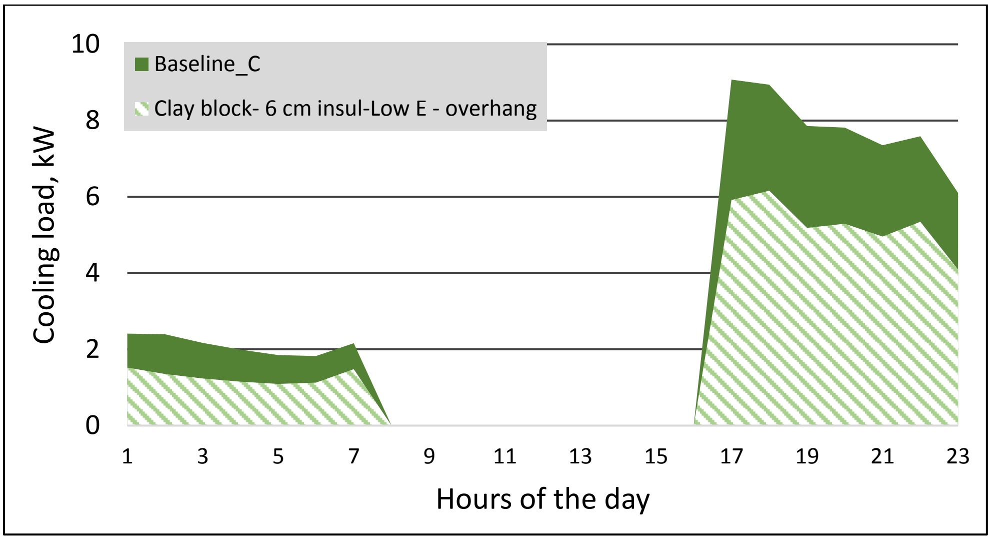


Figure 4-69: Maximum effects of multiple parameters on Flat C

Although orientation has been analysed separately and compared to the baseline energy consumption with the parameters applied, the South-East orientation or as the baseline location shows the minimum energy consumption annually followed by the North-East orientation. A reduction of energy to 2869 and for the North-East 2909kWh when all combinations are applied including the suspended ceiling.

4.7.4 Effects of Multiple Parameters on Flat D

The combination of clay block, 6 cm insulation, low emissivity glazing, with overhang and no suspended ceiling represents the maximum saving parameters, leading to an annual energy saving of 31.85%, reducing the annual energy consumption to 2078.7 kWh and the cooling load from 8.58 to 5.45 kW. Although the cooling load is very high for this flat as it has only two occupants, the energy consumption is very low compared to other flats because of its usage schedules and cooling times. Using 3 cm thick insulation, and with or without the suspended ceiling, the annual energy saving is 30.74%, means an annual saving of just 37.7 kWh compared to 6 cm thick insulation, which once again demonstrates that the 3 cm insulation is the optimum and is the most cost-effective option. Figure 4-70 shows the greatest effect of the parameters on the load compared to the baseline.

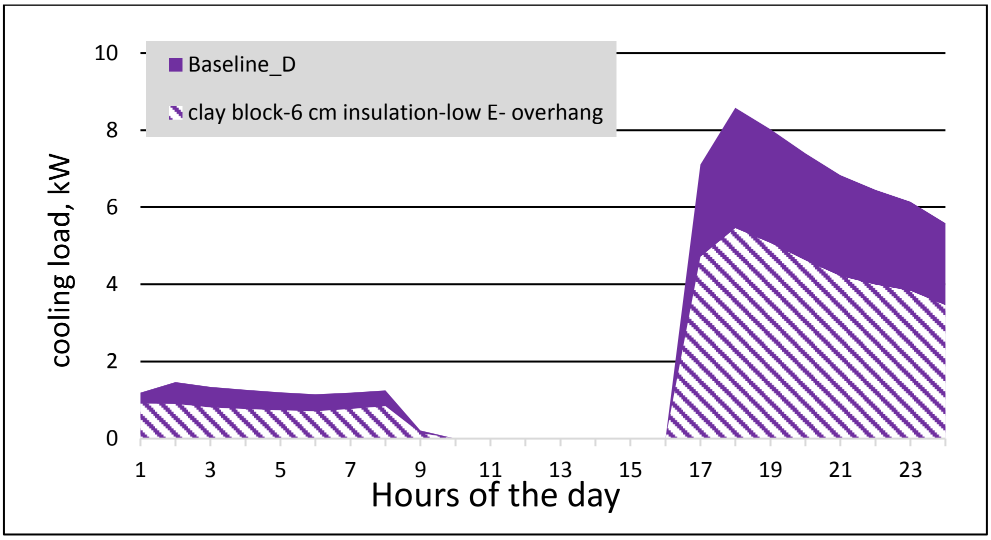


Figure 4-70: Optimum effects of multiple parameters on Flat D

The best orientation was found to be South-West, with the lowest annual energy consumption of 1945.4 kWh. Although the hottest month is July, the results showed that the peak for Flat D was actually on 19th August while for Flat A, Flat B, and Flat C this was on 22nd July because the timing, the scheduling of the cooling requirements and the location of the flat in the building as a whole makes a significant difference.

4.7.5 Effects of Multiple Parameters on the Combined Flats

All parameters have been applied to the combined floor flats' hourly simulations were analysed, the cooling load and the energy used on an hourly basis were determined by assessing the best parameters for the total floor flats on the first floor of the Heja apartment building. This is not as straightforward as the individual operation and scheduling of each of the flats, however.

For the South orientation as the baseline case, a total of 96 different simulations were run to assess the savings for each parameter as applied to individual flats. The top ten parameters are clay block, 6 cm insulation, low emissivity glazing, overhangs and no suspended ceiling, as shown in Figure 4-71, followed by the same parameters with 5 and 4 cm thick insulation, where the energy consumption decreased from 22034 kWh to 17129 kWh, 22.26% saving energy for the first floor only, as shown in the floors' cooling loads in Figure 4-40. In the instance of using 3 cm thick insulation and no suspended ceiling (as the latter clearly does not have any positive influence) giving a 21.39 % annual energy saving. The difference between 3 and 6 cm of insulation is less than 1% annually for the combined parameters mentioned (clay block, 6 cm insulation, low emissivity glazing, overhangs and no suspended ceiling). The other favourable combination of concrete block, 6 cm insulation, low emissivity glazing, overhang and no suspended ceiling) reduces the annual energy consumption to 17643 kWh, representing a saving energy of 19.92% comparing to the base model, which is close to the same combination consumption if changing two parameters, namely the use of clay block and 3 cm thick insulation, whilst keeping the other parameters unchanged . The results show that thicker insulation overrides the effect of the construction blocks, and the optimum thickness is 3 cm for the whole building and, of course, each flat individually.

The minimum energy consumption for the combined flats is with a North-facing orientation, recording 17087.8 kWh energy consumption annually with optimum parameters. This recorded the optimum savings, but with the suspended ceiling in the combination.

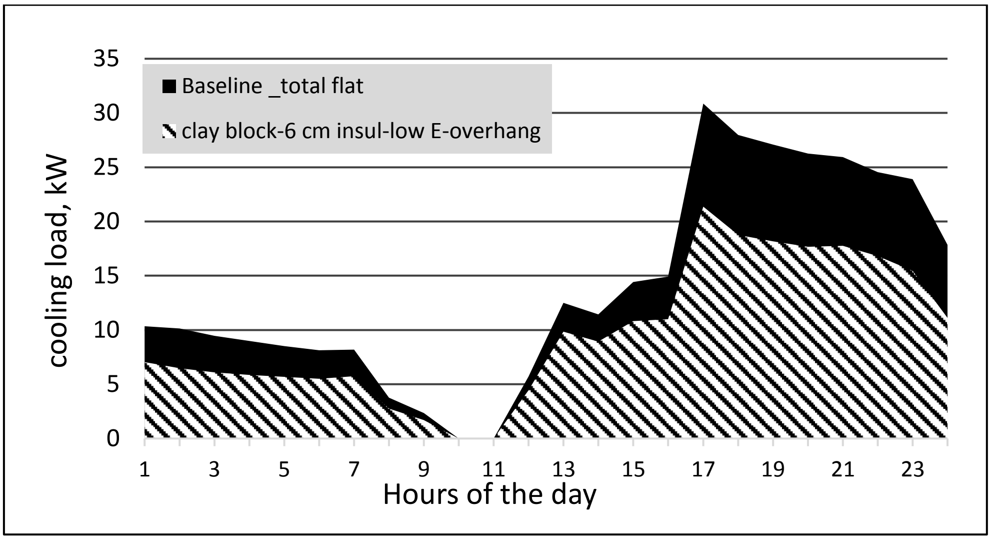


Figure 4-71: Maximum effects of multiple parameters on the combined flats

4.8 Chapter Summary

In summary, adjusting building fabrics building has an obvious impact on the cooling load and annual energy saving. The primary results of the baseline module for the house and the combined flats showed that the cooling system consumes 78% and 79% for the house and the combined flats, respectively, to reach the preferred set temperature of 25°C. Other electrical equipment uses 15% and 7%, and then the lightings consume 7% and 14% for the house and the combined flats, respectively.

The hollow clay brick, 6 cm insulation and adding the suspended ceiling, low emissivity glazing and overhang as parameters, combined with the original (South) orientation of the house building, gives the highest load and energy reductions. It showed that the peak load could be reduced from 17.47 kW to 9.9 kW and the annual energy consumption from 13104 kWh to 9390 kWh. However, if only the clay blocks and 3 cm insulation with the suspended ceiling are added, the load is reduced to 11.16 kW, and the annual energy consumption to 10141 kWh. The difference is relatively small compared to the amount of complexity and number of changes required, such as adding low emissivity glazing and doubling the insulation thickness and with additional external overhangs over the windows. This analysis of the results is a strong indication that the optimum insulation thickness is 3 cm for the external walls, the window replacement should be with low emissivity glazing, but adding external overhangs had no obvious effect on cooling load reduction.

Adding insulation under the roof as well as the suspended ceiling does reduce the cooling load and have a positive effect on annual energy saving, but the save is not significant and is not cost-effective, so the suspended ceiling alone is sufficiently effective and prevents the extra cost of adding insulation. The baseline module daily peak cooling load was selected for the two hottest months of July and August and averaged for design purposes. The average load for the baseline house was shown to be 12.4 kW, covering most of the cooling hours, where the unmet hours totalled only 46 hours out of the 4392 simulated hours. During the unmet hours, the internal temperature raised to 28-29^{o}C for loads between 13-17 kW.

For the apartment project, the cooling load and the annual energy consumption for each flat were different as depending on the number of occupants and operating schedules and the orientation. The primary results showed that the suspended ceiling and clear double glazing have no positive effects, while the overhang has a small impact and the low emissivity glazing has a bit more. The combination of clay brick, 6 cm insulation, low emissivity glazing, overhang and no suspended ceiling was applied for all flats separately, and also for the combined flats. For Flat A, the cooling load reduced from 9.7kW to 7.1kW and the energy consumption reduced from 8621 kWh to 7033 kWh, with annual saving energy of 14.85%. For Flat B, the cooling load was reduced from 6.44 to 5.14 kW and the annual energy consumption from 6175 to 5147 kWh, or in other words an annual energy saving of 12.2%. For Flat C, the annual energy saving was 31.5%, and the maximum cooling load was reduced from 9.63 to 5.45 kW, while for Flat D the annual energy saving was 31.8%, and the cooling load was reduced from 8.58 to 5.45 kW.

The combined flats were also considered, and applying the same parameters the annual energy consumption was reduced from 22034 to 17129 kWh, recording a saving of 22.3% for the first floor, whilst 3 cm thick insulation resulted in a 21.4% annual saving which is less than a 1% difference. On this floor, it was observed for every flat that adding the suspended ceiling had a negative impact on cooling load and energy saving, so it is clearly unworthy while adding suspended ceilings in any of the flats with the exception of the top floor, which could well behave more like the single house and because it has greater exposure to the external environment and solar irradiation. Using 3 cm instead of 6 cm of insulation and keeping the other parameters constant for each of the flats and, indeed, the combined flat cases did not make any significant difference in cooling load reduction and the annual energy saving, so the 3 cm insulation is thus considered the most cost-effective solution. The suspended ceiling shows no apparent advantage when installing in the middle floors. From analysing the simulation results for the effect of the parameters on the flat building, the combination of [clay block-3cm insulation-low emissivity glazing] is the optimum among all parameters applied taking into consideration the number of changes and the bulky sizing of the changes and the cost.

The optimum parameters for the house were different from those of the flats, regardless of the orientation of the building. The most effective for the house was shown to be the use of clay blocks, 3 cm insulation and suspended ceiling whilst for the flats the most effective parameters were the use of clay blocks, 3 cm insulation and low emissivity glazing.

Each separate flat and the combined flats' daily peak loads were selected for the two hottest months of July and August and then averaged for design purposes. For Flat A, the daily peak loads were averaged, resulting in a reduction from 9.7 to 7.88 kW. The averaged load covers almost all the cooling hours apart from 82 of 4392 simulated hours. During the unmet hours, the temperature in Flat A was found to rise to 26-29^{o}C. Flat B peak loads were averaged, and the baseline load was found to reduce from 6.44 to 5.1 kW, with 133 unmet hours out of a total of 4392 hours, during which the internal temperature of the unmet hours was found to rise to 26-29^{o}C. Flat C's peak average showed a reduction to 7.35 kW with 100 unmet hours out of 4392 hours, during which the temperature would be between 26-28^{o}C. Flat D's averaged peaks were reduced from 8.6 to 5.39 kW, where this unmet load was found to raise the internal temperature to over 30^{o}C. The reason for the large difference between the averaged peak and the unmet peaks was due to the two days when there was no cooling in operation in the flat.

Finally, the combined flats were assessed and the load reduced from over 30 to 21.15 kW. The difference between the peak unmet loads was quite large due to the effects of the operating schedules of Flat C and D on the floor's total cooling. There were 200 unmet hours during which the temperature was found to rise to over 29°C.

Another averaged method was used for the combined floor flats, a method of two hot months week peaks averaged cooling load was used, this is raised the averaged load level to 26.8 kW, by using this method will cover almost all cooling load hours except 31 hours. It is vital that if the cooling was to supply to one building with unchanged cooling load pattern then it is highly beneficial to use and predict the best coverage for cooling hours. The average daily peaks method is a good approach if multi zones combined into one single zone to provide cooling. If there were several zones are not regularly operated such as the total floor flats, and then the method of weekly average peak should be used, the non-uniform load pattern came from Flat C and D cooling supply weekend schedules.

Chapter 5: Dew Point Cooling System: Design, Optimization and Application

5.1 Introduction

This chapter describes the design and optimization of the dew point indirect evaporative cooling system and its application for both case study buildings. Figure 5-1 shows the schematic diagram of designing the dew point heat exchanger for both case studies. The objectives of the chapter are as below:

1- Modelling the dew point cooler depending on the literature review and previous reliable studies, using MATLAB software. A set of governing formulas for air psychometrics will be employed using the epsilon – Number of Transfer Units (ϵ-NTU) method for the heat exchangers. The bespoke code written for this study is shown in Appendix C. The coding was assisted by an expert technician, using previously published formulae [125],[126]. It can be used for all weather conditions to assess the feasibility of dew point cooling system. As for a certain dimension of the heat exchanger, the simulation code takes the inputs from outside temperature and humidity and gives water consumption and cooling capacity of the cooler; then the output will be combined with the selected building 's cooling load to verify the final sizing of the heat exchanger.

2- Analysing the computerized model for best cooling output using the hottest month of the year's hourly data to determine the optimum geometric and physical parameters for the cooler. Then, the optimized model will be enhanced based on the preferred cooling output and water consumption.

3- Employing the hourly cooling load output of the case studies from the previous chapter and combine it with the hourly cooling output of the optimized dew point system for the season, then determining the heat exchanger size for the baseline cases.

4- Applying and analysing the effects of the building parameters, both individually and together, on the size of the heat exchanger required for the entire cooling season to determine the size of the heat exchanger required. Based on this maximum size, total water consumption then will be calculated.

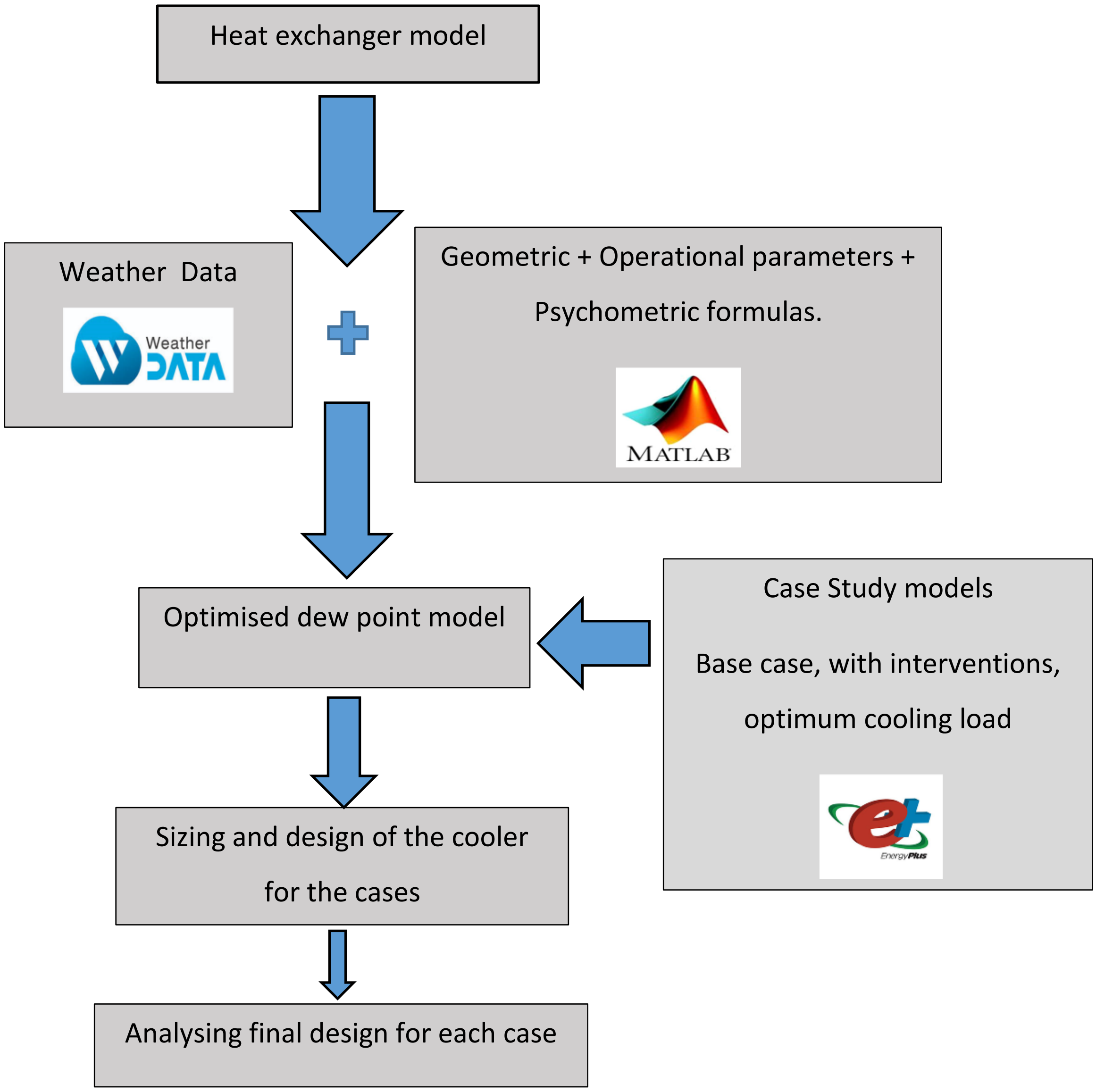


Figure 5-1: Dew point heat exchanger design methodology diagram

5.2 Conceptual Design of Dew Point Cooler

A conceptual design, including geometrical and operational parameters, was prepared in accordance with the previous literature and research. This proposed design includes the geometrical (length and height of channels, thickness and material of the plates) and operational parameters (air velocity and air ratio) as some of the bases for the modelling, as follows.

5.3 Dew Point Evaporative System Modelling

A computerised model was developed using the MATLAB software to represent the dew point cooling system, in accordance with the literature review and a previously published study [125][126]. This previous study has already been validated using reliable experimental data [166]. The system was modelled theoretically, as based on theoretical calculations of the heat transfer between the channels of the heat exchanger. The latter forms the main part of the cooler and is constituted of multiple layers of flat plates made from very thin aluminium and covered on one side by a piece of very thin fabric to hold water when wetted by the water sprayer from above.

The model is based on 100% outside air being delivered into the building. The computerised model developed would (a) determine the system's performance under different variables, (b) determine the optimal system configuration, and (c) determine an appropriate system design and optimal operational parameters.

5.3.1 The Mathematical Formulas Representing the System

A one-dimensional model has been developed to solve the temperature, enthalpy and humidity distributions inside the indirect evaporative air cooler. A mathematical derivation of the governing equations is presented. A number of assumptions are made to simplify the solution: (1) the cooler is assumed to be well insulated; (2) longitudinal thermal conduction in the plate wall in the *x*-direction is neglected; (3) the heat and mass transfer coefficients inside each passage are constants; and (4) the liquid side of the air-water interface offers negligible resistance to heat transfer, so that the interface temperature is saturated at the water film temperature (tf). Heat and mass balance equations are applied to the dry and wet channels. The passages to solve the indirect evaporative cooler problem are addressed via the (ϵ-*NTU*) method.

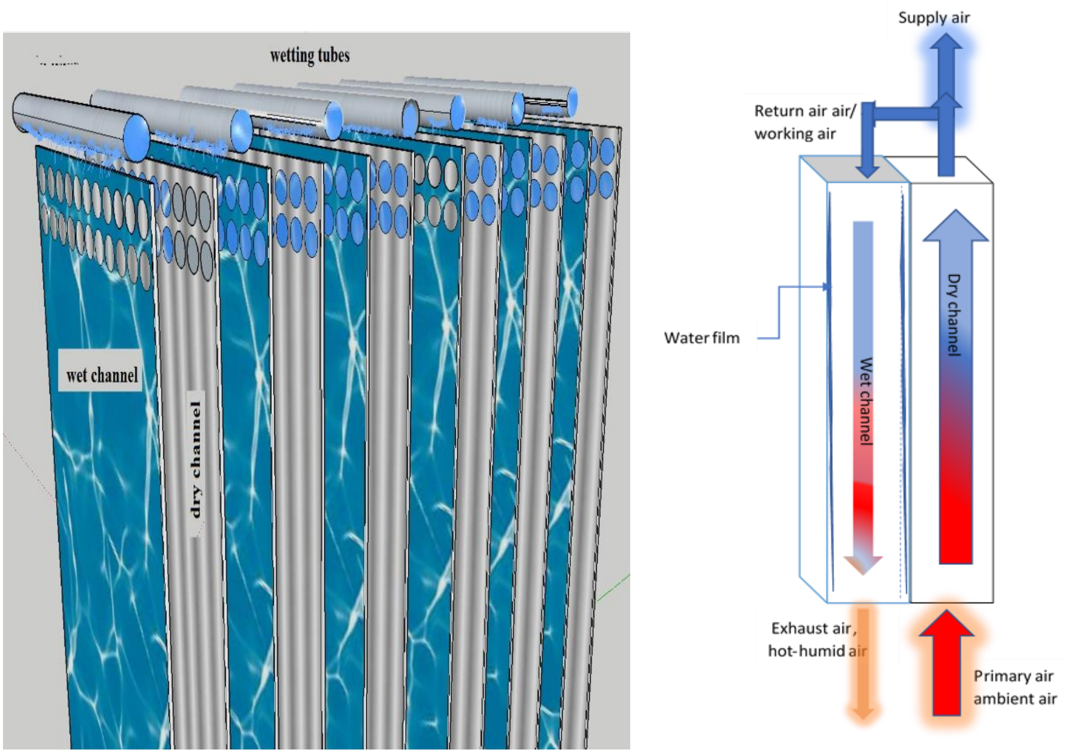


Figure 5-2: Airflow schematic diagram of a dew point air cooler

It can be noted from Figure 5-2 that a direct implementation of Epsilon ($\epsilon - NTU$) is a very well-known method of addressing sensible heat transfer problems and offers an approach and solution to heat exchanger problems and heat transfer rate subjects[125],[167]. The heat transfer between two fluids is given by:

$$Q = UA(T_{hot} - T_{cold}) \quad (5\text{-}1)$$

Where:

Q = is the heat transfer rate in W or kW

U = total heat transfer coefficient of the wall between the wet and dry channels in W/m^{2}K

A = Area of heat exchanger plate, m^2

T_{hot}*= Hot fluid temperature, K*

T_{cold}*= Cold fluid temperature, K*

The overall plate wall heat transfer coefficient is given by:

$$U = \frac{1}{\frac{1}{h_{cold}} + \frac{\alpha}{k} + \frac{1}{h_{hot}}} \quad (5\text{-}2)$$

Where:

α = wall thickness, m

k = wall plate conductivity, W/m K

h_{hot} *= convective heat transfer coefficient of hot fluid, W/m^2 K*

h_{cold} *= convective heat transfer coefficient of cold fluid W/m^2 K*

The maximum heat transfer of a heat exchanger is given by:

$$Q_{max} = C_{min}\left(T_{hot_{in}} - T_{cold_{in}}\right) \quad (5\text{-}3)$$

Where:

Q_{max} *= The maximum possible heat transfer rate*

$T_{hot_{in}} - T_{cold_{in}}$*= maximum temperature drop*

C_{min} *= Minimum from the lower heat capacity rates of cold and hot air i.e. min (C_{cold}, C_{hot})*

The effectiveness, epsilon *(*Σ) is given by:

$$\Sigma = \frac{Q}{Q_{max}} \quad (5\text{-}4)$$

Where:

Q = the actual heat transfer rate (W)

Q_{max}= *maximum possible heat transfer rate (W)*

For the heat exchangers, epsilon is a value that falls within the bounds $0 \leq \varepsilon \leq 1$

$$Q = \varepsilon\, C_{min}\left(T_{hot_{in}} - T_{cold_{in}}\right) \tag{5-5}$$

$$\varepsilon = f(NTU, C_r) \tag{5-6}$$

Where:

$C_r = ratio\ of\ Cmin\ to\ Cmax = \frac{C_{min}}{C_{max}}$,

$NTU =\ the\ number\ of\ thermal\ unit\ transferred$

The epsilon equation has different forms; for the counter-flow used in this study, the heat exchanger the formula pattern is as following [125]:

When Cr is < 1

$$\varepsilon = \frac{1-\exp[-NTU\ (\ 1-C_r)]}{1-C_r\ exp[-NTU(1-C_r)]} \tag{5-7}$$

In the indirect evaporative cooling system, the distribution of the temperatures and enthalpy in the dry and wet channel and the temperature of the dry air stream was connected to the enthalpy of the wet channel by a relationship based on a unique enthalpy gradient:

$$M\, C_p\, (T_i - T_o) = M^*\, [(\, h_s(T_i) - h_s\, (T_o)\,] \tag{5-8}$$

$$M^* = M C_p \frac{(\, T_i - T_o)}{h_s\, (T_i) - h_s(T_o)} \tag{5-9}$$

$$M^* = M \frac{C_p}{a} \tag{5-10}$$

Where:

$M^* = modified\ mass\ flow\ rate\ in\ the\ dry\ channel$

$C_p = specific\ heat\ capacity\ of\ the\ air$ *J/kg.K*

$a = temperature\ and\ enthalpy\ saturation\ line$ *J/kg.K*

T_i = *wet channel inlet air temperature* ^0C

$T_o =$ $channel\ exit\ air\ temperature$ ^0C

$h_s(T_i) = enethalpy\ of\ the\ inlet\ air\ of\ the\ wet\ channel$

$h_s(T_o) = air\ saturation\ enethalpy\ at\ the\ dry\ temperature$

The cooling effectiveness of the indirect evaporative cooling system depends on the wet-bulb effectiveness, which can be expressed as below:

$$\varepsilon_{wb} = \frac{T_{db,1} - T_{db,2}}{T_{db,1} - T_{wb,1}} \tag{5-11}$$

Where:

ε_{wb} *: Wet bulb effectiveness ;*

$T_{db,1}$ *: Intake primary air-dry bulb temperature,* ^oC

$T_{wb,1}$ *: Intake secondary air wet bulb temperature,* ^oC

$T_{db,2}$ *: Product air dry bulb temperature,* ^oC

The dew point effectiveness is defined as:

$$\varepsilon_{dp} = \frac{T_{db,1} - T_{db,2}}{T_{db,1} - T_{dp.1}} \tag{5-12}$$

Where:

ε_{dp} = dew point effectiveness

$T_{dp,1}$ = intake primary air dew point temperature, ^{o}C

When the intake air for the system is derived from indoor air, the cooling capacity is defined as [125]:

$$Q_{\text{cooling,}} = N_{ch}.\ C_{p_{air}}\ .\ (1 - X)\ .\ m^{\circ}\ \left(T_{db,in} - T_{db,out}\right) \tag{5-13}$$

Where:

$Q_{cooling}$ = cooling capacity of evaporative cooler, W

N_{ch} = number of channels

X = air ratio

$C_{p_{air}}$= specific heat of air at constant pressure, kJ/(kg k)

M° = mass flow rate in the channel kg/sec

$T_{db,in}$ = dry-bulb temperature of intake air ^{o}C

$T_{db,out}$ = dry-bulb temperature of supply air ^{o}C

The coefficient of performance (COP) describes the ratio of sensible cooling capacity achieved to total power consumption by the air fan:

$$COP = \frac{Q_{\text{cooling}}}{Q_{in}} \tag{5-14}$$

Where:

Q_{in}= Electrical Power consumption, W

The water consumption of the indirect evaporative cooling systems depends on the airflow, the dry-bulb and wet-bulb temperature difference of the intake air and the effectiveness of the evaporator medium. In an ideal situation, the water consumption or evaporation rate can be calculated by multiplying the moisture difference in the secondary air inlets and outlets by the secondary air mass flow rate and then dividing by the density of water, as follows:

$$V_w = N_{ch} \,.\, m° \,.\, X \,(\, w_3 - w_1) * 3600 \tag{5-15}$$

Where:

V_w = water evaporation, l

N_{ch} = number of (wet-dry) air channels

$m°$= mass flow rate

X = air ratio

w_1= inlet moisture content of secondary air kg/kg (dry air)

w_3 = outlet moisture content of secondary air kg/kg (dry air)

5.3.2 Input Parameters

Two air ratios of 0.4 and 0.5, two channel gaps of 3.5 and 4.5 mm, two cooler heights of 1.0 and 1.2 meters, and three recommended velocities of 1.5, 2.0 and 3.0 m/s were selected, as shown in Table 5-1. The selection resulted in twenty-four simulation runs. A small pack of plates was selected for the simulating runs; the channel numbers were limited to 44 dry and wet channels (22 pairs/pack), and real weather data have been used for the simulation.

Table 5-1: Recommended geometrical and physical parameters

Air ratio	Channel gap mm	Height m	Velocity m/s	No of channel
0.4	3.5	1	1.5	44
0.5	4.5	1.2	2	44
			3	44

Table 5-2: Enhancing dew point cooler's parameters MATLAB simulation.

runs	Air ratio	Gap, mm	Height mm	Velocity m/s	Air mass flow rate kg/s
run 1	0.4	3.5	1000	1.5	0.07
run 2				2	0.09
run 3				3	0.14
run 4			1200	1.5	0.07
run 5				2	0.09
run 6				3	0.14
run 7		4.5	1000	1.5	0.09
run 8				2	0.12
run 9				3	0.18
run 10			1200	1.5	0.09
run 11				2	0.12
run 12				3	0.18
run 13	0.5	3.5	1000	1.5	0.07
run 14				2	0.09
run 15				3	0.14
run 16			1200	1.5	0.07
run 17				2	0.09
run 18				3	0.14
run 19		4.5	1000	1.5	0.09
run 20				2	0.12
run 21				3	0.18
run 22			1200	1.5	0.09
run 23				2	0.12
run 24				3	0.18

The output from the simulated model was analysed to select and assess the effects of a given parameter while the other parameters were kept unchanged to determine the optimal value from twenty-four runs and then basing the design accordingly.

5.4 Results and Analysis

5.4.1 Channel Gap Effect

Table 5-3 shows the comparison of the two channel gaps, 3.5 and 4.5 mm high, when the length was kept constant and where three velocities were tested. This table shows the output of runs 1, 2, and 3 and 7, 8, and 9 from Table 5-2.

Table 5-3: Channel gap comparison analyses

	Channel 3.5 mm			Channel 4.5 mm		
Air Velocity m/s	**1.5**	**2**	**3**	**1.5**	**2**	**3**
Max. cooling kW	1.08	1.26	1.59	1.12	1.30	1.53
Av. kW	0.65	0.76	0.96	0.67	0.78	0.94
Min. kW	0.19	0.23	0.3	0.20	0.24	0.30
Water Av. l/hr	0.79	1.01	1.52	0.979	1.31	1.96
Total water/ month	594.2	753.7	1138.4	729.8	977	1465.4
Ave. (32-40°C) QCC, kW	0.82	0.96	1.21	0.85	0.99	1.17
Water l/hr (32-40°C)	1.03	1.31	1.98	1.27	1.7	2.559
Volume m^3	0.08825	0.08825	0.08825	0.11025	0.11025	0.11025

Increasing the channel gap means increasing the size of the cooler; however, this needs to be limited because the physical size of the dew point cooler is large, and the research aims to decrease it. For the low velocity, 1.5 m /s, the 4.5 mm channel gap offers slightly greater cooling but increases the water consumption rate. For the higher velocity, 3m/s, a 3.5 mm channel gap offers the maximum cooling. The 44 air channels were simulated (22 dry/wet pairs) while the width of the cooler was kept constant at 0.5 m, and the length of the channel was 1 m, resulting in a length/channel gap ratio of 285 and 222 respectively [117] [168]. This ratio is still within that of previous studies of air velocity in the channels, which as shown in Table 5-3 is relatively slow at 1.5 m/s. Hourly standard energy plus weather data for July was used for the simulation, the results of which showed that for the 744 hrs of simulation, the average cooling with a 3.5 mm gap was 0.65kW, while the average water consumption was 0.79 l/hr. However, the 0.45 mm gap provided a 0.67 kW cooling load and water consumption of 0.97 l/hr.

The maximum cooling output for the 3.5 mm gap was found to be 1.08 kW, whilst for the 4.5 mm gap, the cooling output was 1.12 kW using a 1.5 m/s air flow rate. This is not a large difference in terms of cooling outputs, but the water consumption in each case would play a role depending on the availability of the local water supply. Monthly water consumption was calculated for each, where the consumption by the 3.5 mm for the entirety of July was 594.2 litres, which was less than the 4.5 mm gap at 729.8 litres. Another assessment was made at a higher temperature, between 32^{o}C and 40^{o}C, covering 368 hrs of the month and when the cooling demand was at a peak. Under the slowest air velocity of 1.5 m/s, the 3.5 mm gap provided an average of 0.81 kW cooling capacity with an average of 1.03 litres/hr of water, while the 4.5 mm channel gap provided 0.84 kW and a consumption rate of 1.27 litre/ hr, or in other words a much higher water consumption for almost the same cooling output.

When the velocity was increased to 2 and 3 m/s for each of the above channel gaps, the average cooling outputs were 0.95 and 1.2 kW for the 3.5 mm gap and 0.98 and 1.17 kW for the 4.5 mm gap, respectively. The average water consumption rate for the two velocities and the temperature range (32-40^{o}C) for each channel were 1.31 and 1.98 litres/hr and 1.70 and 2.55 litres/hr, respectively.

There is a clear indication that the cooling output increases with air velocity and the 3.5 mm gap is demonstrably a better choice for the output than the 4.5 mm channel gap. In analysing velocities against water consumption over the temperature intervals discussed, a 3 m/s is undesirable as the water consumption rate is increased for a smaller output, as cooling capacity in the 4.5 mm channel is lower than the 3.5 mm gap for a given velocity. So, for the temperature range of 32-40^{o}C and the two channels gaps (3.5 mm and 4.5 mm), the 3.5 mm has a better output when the velocity is under 2 m/s, giving 0.95 kW for a 1.31 litres/hr flow rate.

5.4.2 Length Comparison

Two different lengths were used in this study for the cooler, 1 and 1.2 m, respectively, whilst maintaining a channel gap of 3.5 mm and an air ratio of 0.4, with different velocities of 1.5 and 3 m/s.

Table 5-4: Comparison of two different channel length, with a channel gap of 3.5 mm and an air ratio of 0.4

	Channel 1 m			**Channel 1.2 m**		
	1.5 m/s	2 m/s	3 m/s	1.5 m/s	2 m/s	3 m/s
Max cooling, kW	1.08	1.26	1.59	1.07	1.34	1.74
Average, kW	0.65	0.76	0.96	0.65	0.81	1.04
Minimum, kW	0.19	0.23	0.30	0.19	0.24	0.32
Water Average l/hr	0.80	1.02	1.54	0.76	1.02	1.54
Total l/hr	594.8	753.7	1138.4	561.2	753.7	1138.6
Average (32-40°C) Cooling, kW	0.65	0.76	0.967	0.66	0.81	1.05
Water l/hr (32-40°C)	0.80	1.01	1.53	1.75	1.019	1.538
Volume m^3	0.08825	0.08825	0.08825	0.1059	0.1059	0.1059
kW/ m^3 (volume)	7.36	8.61	10.95	6.23	7.64	9.91

The length/channel gap ratio for the 1 and 1.2-metre lengths were 285 and 342, respectively. The literature suggests that the length of the channel should be between 100-300 times the dimension of the channel gap, and beyond that value the length would not be very effective and will not have a major effect on the cooling, if the material and pressure drop have taken into account The length/channel ratio of a 1.2 m length is slightly better than the 1 m length for the cooling output, which confirms the researcher's findings that a 300 times channel length does not favour cooling if other parameters are taken into account.

Figure 5-3 shows the effects of channel height on cooling output and the hourly rate of water consumption for the 44-channel cooler. The rate of water evaporation is not particularly affected by increasing the length from 1 to 1.2 metres, although the water consumption rate for temperatures between 32-40°C for July shows a slight increase in the rate of water evaporation in the 1.2 length for the slow speed, as the air still exchanges heat with the dry side and promotes evaporation due to the slow air flow rate.

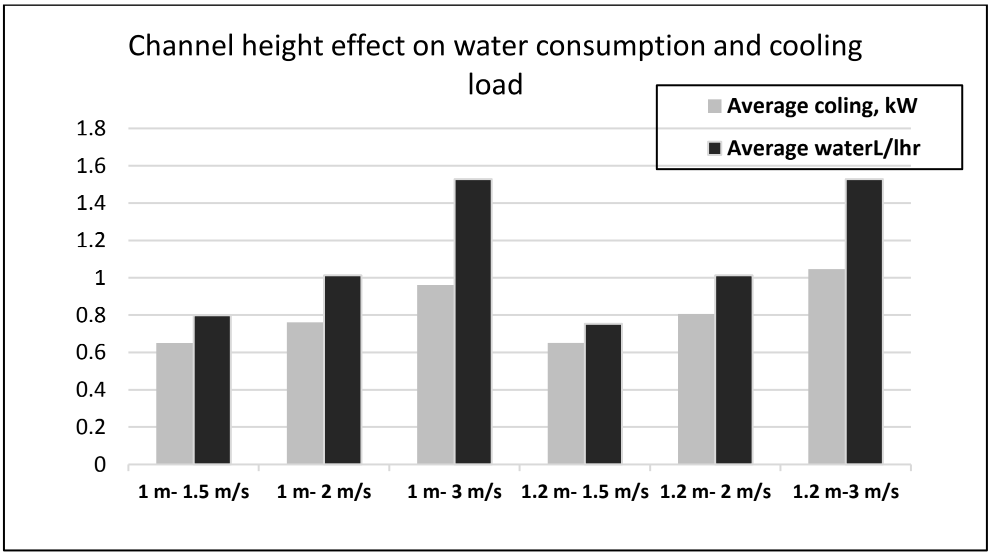


Figure 5-3: Effect of height on cooling capacity and water consumption rate in July during the hotter part of the day

5.4.3 Air Ratio

Two different ratios for working/intake air were considered for the simulation. For this, ratios of 0.4 and 0.5 of working/primary air were used. The results of the simulations for the air velocities show that the 0.4 working/primary air ratio for a 3 m/s flow gave the best cooling output, as shown in Figure 5-4**.**

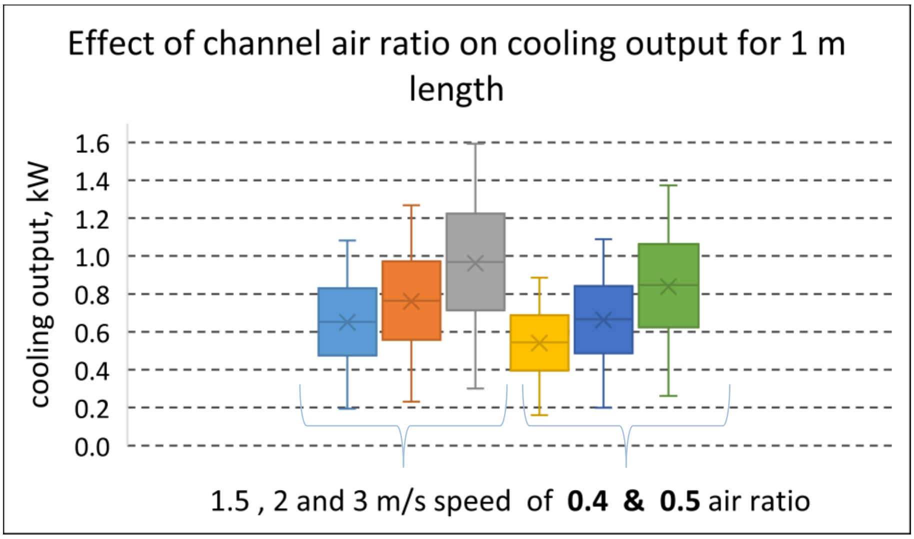


Figure 5-4: Effect of air ratio effect on cooling output

Table 5-5: Effect of air ratio on a 1 m channel length and a 3.5 mm gap with different air velocities, shows the results of the simulation when two air ratios were compared for the 744 hours that covered the 31 days of July. Although the cooling output for the 0.4 ratio gives a better output, the 0.5 ratio shows greater evaporation and the average hourly water consumption increases with the speed of the air in the channel.

Table 5-5: Effect of air ratio on a 1 m channel length and a 3.5 mm gap with different air velocities

Air ratio	0.4	0.4	0.4	0.5	0.5	0.5
Air velocity m/s	1.5	2	3	1.5	2	3
Max cooling kW	1.082	1.267	1.593	0.886	1.089	1.372
July Average Cooling kW,	0.650	0.760	0.961	0.541	0.663	0.838
Average water consumption l/hr	0.799	1.012	1.528	0.885	1.189	1.795

5.4.4 Optimization and Selection of Simulation Parameters

The rate of water evaporation and cooling output of the cooler are two main principles for selection of this type of cooling systems, and they are different parameters. To find the best result among the simulated parameters and that could be used for designing the dew point heat exchanger, the extreme month hourly simulated were used, summed and normalised. A multi-objective optimisation formula was applied using MATLAB with a weighting factor between the two parameters of water consumption and cooling output. This is to make it into single objective, classify and set the best simulation according the selected and desired weighting factor. Table 5-6 shows all used weighting factors to classify the total simulations according the cooling output and the water consumption so that to be used and coupled with the building loads requirement.

Weighting factor (wi)=Cooling output + Water evaporation rate (5-16)

$$Objective\ function = \sum_{1}^{2} wi.fi(x) \tag{5-17}$$

Where:

wi, is the weighting factor ($0 \leq wi \leq 1$)

$fi(x)$, is the objective function for min water consumption and max cooling output.

Table 5-6: Weighting factor and trade-off between water and cooling output

	The Dominant	
(Weighting factor) Energy% + water%	Cooling Energy %	water %
1.0	100.	0.0
0.9+0.1	90	10
0.8+0.2	80	20
0.7+0.3	70	30
0.75+0.25	**75**	**25**
0.6+0.4	60	40
0.5+0.5	50	50
0.4+0.6	40	60
0.3+0.7	30	70
0.2+0.8	20	80
0.1+0.9	10	90

Table 5-7 shows all 24 classified simulations according to the weighting factors and trade-off between water and the cooling output of the dew point cooler heat exchanger, each simulation's number refers to a number of parameters that are used in the simulation which was prepared in MATLAB. Each simulation models that were previously analysed in terms of their best outputs for cooling energy, length, channel gap, and air ratio with the three air velocities previously discussed, Table 5-7 lists all 24 dew point simulations for July according the required arrangement.

Table 5-7: Simulation ranking and the normalised values according to the weighting factor between desired cooling output and water consumption.

										Simulation No and normalised values , from Right ot left																
24	**23**	**22**	**21**	**20**	**19**	**18**	**17**	**16**	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	WF	Cooling %	water %
13	16	19	22	1	4	14	7	20	17	10	23	2	8	5	21	15	11	24	18	9	3	6	12	**1.0**	**100**	**0**
0.516	0.537	0.563	0.604	0.620	0.622	0.632	0.645	0.655	0.670	0.693	0.716	0.725	0.752	0.770	0.776	0.800	0.821	0.868	0.870	0.897	0.917	0.997	1.000	**1.0**	**100**	**0**
13	16	19	22	14	20	1	7	4	17	23	10	2	21	8	15	5	11	24	18	9	3	12	6	**0.9**	**90**	**10**
0.550	0.568	0.572	0.609	0.632	0.639	0.653	0.658	0.660	0.666	0.694	0.701	0.727	0.732	0.734	0.762	0.768	0.797	0.814	0.825	0.845	0.875	0.938	0.946			
19	13	16	22	20	14	17	7	23	1	21	4	10	8	15	2	24	5	11	18	9	3	12	6	**0.8**	**80**	**20**
0.581	0.583	0.599	0.614	0.622	0.633	0.662	0.670	0.671	0.685	0.687	0.698	0.708	0.717	0.724	0.729	0.760	0.765	0.772	0.780	0.794	0.832	0.876	0.896			
19	20	13	22	16	14	21	23	17	7	15	8	24	10	1	2	18	4	9	11	5	3	12	6	**0.7**	**70**	**30**
0.590	0.605	0.617	0.619	0.631	0.633	0.642	0.648	0.659	0.682	0.686	0.699	0.706	0.716	0.717	0.731	0.735	0.735	0.743	0.747	0.763	0.790	0.815	0.846			
19	**13**	**20**	**16**	**22**	**14**	**23**	**17**	**21**	**7**	**1**	**15**	**8**	**10**	**4**	**2**	**24**	**18**	**11**	**5**	**9**	**3**	**12**	**6**	**0.75**	**75**	**25**
0.586	**0.600**	**0.614**	**0.615**	**0.617**	**0.633**	**0.660**	**0.661**	**0.664**	**0.676**	**0.701**	**0.705**	**0.708**	**0.712**	**0.717**	**0.730**	**0.733**	**0.757**	**0.760**	**0.764**	**0.768**	**0.811**	**0.845**	**0.871**			
20	21	19	22	23	14	15	13	24	17	16	8	18	9	7	11	10	2	3	1	12	5	4	6	**0.6**	**60**	**40**
0.589	0.597	0.600	0.624	0.625	0.633	0.648	0.650	0.651	0.655	0.662	0.681	0.690	0.691	0.695	0.723	0.724	0.733	0.748	0.750	0.753	0.760	0.773	0.795			
21	20	24	23	19	15	22	14	9	18	17	8	13	12	16	11	3	7	10	2	6	5	1	4	**0.5**	**50**	**50**
0.552	0.572	0.597	0.603	0.609	0.610	0.629	0.633	0.640	0.645	0.652	0.663	0.684	0.691	0.694	0.698	0.705	0.707	0.731	0.735	0.745	0.757	0.782	0.811			
21	24	20	15	23	9	18	19	12	14	22	8	17	3	11	6	13	7	16	2	10	5	1	4	**0.4**	**40**	**60**
0.507	0.543	0.556	0.572	0.580	0.589	0.600	0.618	0.629	0.633	0.634	0.646	0.648	0.663	0.673	0.694	0.717	0.719	0.725	0.737	0.739	0.755	0.814	0.849			
21	24	15	9	20	18	23	12	3	19	8	14	22	6	17	11	7	2	10	13	5	16	1	4	**0.3**	**30**	**70**
0.462	0.489	0.534	0.537	0.539	0.554	0.557	0.567	0.620	0.627	0.628	0.633	0.639	0.644	0.644	0.648	0.732	0.739	0.746	0.751	0.752	0.757	0.846	0.887			
21	24	9	15	12	18	20	23	3	6	8	11	14	19	17	22	2	7	5	10	13	16	1	4	**0.2**	**20**	**80**
0.418	0.434	0.486	0.496	0.505	0.509	0.522	0.534	0.578	0.594	0.610	0.624	0.633	0.636	0.641	0.645	0.741	0.744	0.750	0.754	0.784	0.788	0.879	0.924			
21	24	9	12	15	18	20	23	3	6	8	11	14	17	19	22	2	5	7	10	13	16	1	4	**0.1**	**10**	**90**
0.373	0.380	0.434	0.444	0.458	0.464	0.506	0.512	0.535	0.543	0.592	0.599	0.634	0.637	0.645	0.650	0.743	0.747	0.757	0.761	0.818	0.820	0.911	0.962			

As water is not the main issue for and there is enough water to meet demand for Kurdistan, direct evaporative cooling is still used in residential buildings. The problem is rather one of electricity and power consumption, so the priority in the selection, and thus the greater weight, is given to the cooling output. The desired case of a 75% cooling output (dominant) and 25% water consumption was selected. Table 5-6 shows the run number which represents the parameter selection listed from 1 to 24 according to the desired modelling for each percentage. For the 75% cooling output and 25% water consumption, run no. 6 was found to be optimal, which has a 0.4 air ratio, 3.5 mm channel gap, 1.2-metre length and 3 m/s airflow velocity, followed by run no. 12, as shown in Table 5-2. Therefore, the simulation for a 3.5 mm gap, 0.4 air ratio, and 1.2 m length will be used in the following steps to determine the amount of water required, and the sizing of the heat exchanger needed to provide comfort to a residential building in Erbil.

5.4.5 Dew Point and Wet Bulb Effectiveness

The dew point cooling system with the selected physical and operational parameters shows reasonable effectiveness for both the dew point and wet bulb. The average wet bulb effectiviness for the entire cooling season reached 106%, whilst the dew point was slightly reduced, recording an average of a 66.8% efficiency. These two effectiveesses are better than those reported in the literature, especially when this model was tested for cooling for the required season, namely from April to September and covering 4392 hours. When cooling is preferred, the system is very efficient, and its effectiveness can reach 108.9% and 72.8% for the wet bulb and dew point, respectively, because of the high humidity on some days that decreases the dew point’s effectiveness. These values were obtained by using the same hourly weather data that was used for the building and for the simulations of the dew point cooler, which were later optimised.

5.5 The Optimum Design of the Dew Point Heat Exchanger

A model the used a 44 dry and wet channel dew point cooler was simulated with the dominant energy of 75% and 25% use of water. A length of 1200 mm, 3.5 mm channel gap and 500 mm width with a 0.4 air ratio and 3 m/s airflow rate were used to model the sizing of this particular dew point cooling heat exchanger.

Erbil city's hourly weather data from April to the end of September, covering 4392 hours for the simulation, was used to gain hourly cooling output using the hourly dry bulb temperature, DBT, and the hourly ambient relative humidity, RH. The result of the simulation would then be used to size any hourly cooling load profile to determine the amount of water required to cool the building, and the number of heat exchangers (size) required. Each pack of the dew point heat exchangers consisted of 22 pair of dry/wet channels that were the equivalent of a volume of 0.1059 m^3, as shown in Table 5-8. Figure 5-5 and Figure 5-6 show the cooler parts and geometric dimensions.

Table 5-8: Dew point heat exchanger design sizing.

Plate type	Length mm	Width mm	**Channel gap dry/wet, mm**	**No of channel**	**Surface area, m^2**	**Volume m^3**	**Mass flow kg/s**
Aluminium covered with fabric	1200	500	3.5	44	0.6	0.1059	0.14091

There is possibility of legionella growth with direct evaporative cooling systems, because of the direct contact with the water droplets. However, dew point evaporative cooler uses water in its cooling process, but the is no possibility and risk of Legionella infection. The physical design of the system prevents spreading this disease, as there is non-direct contact of water droplets with the supply air in the cooling process [169].

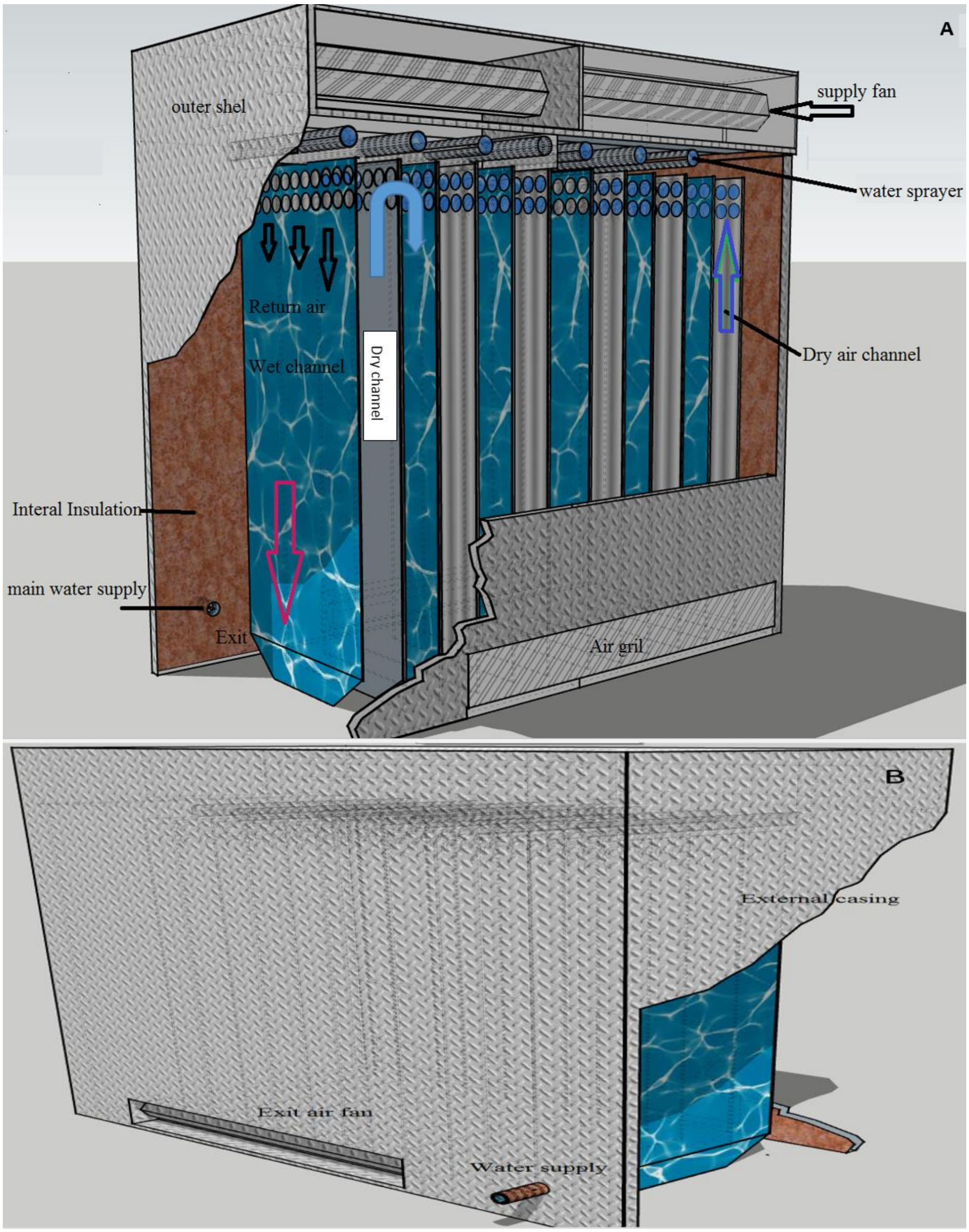


Figure 5-5: Dew point cooler heat exchanger (front and back)

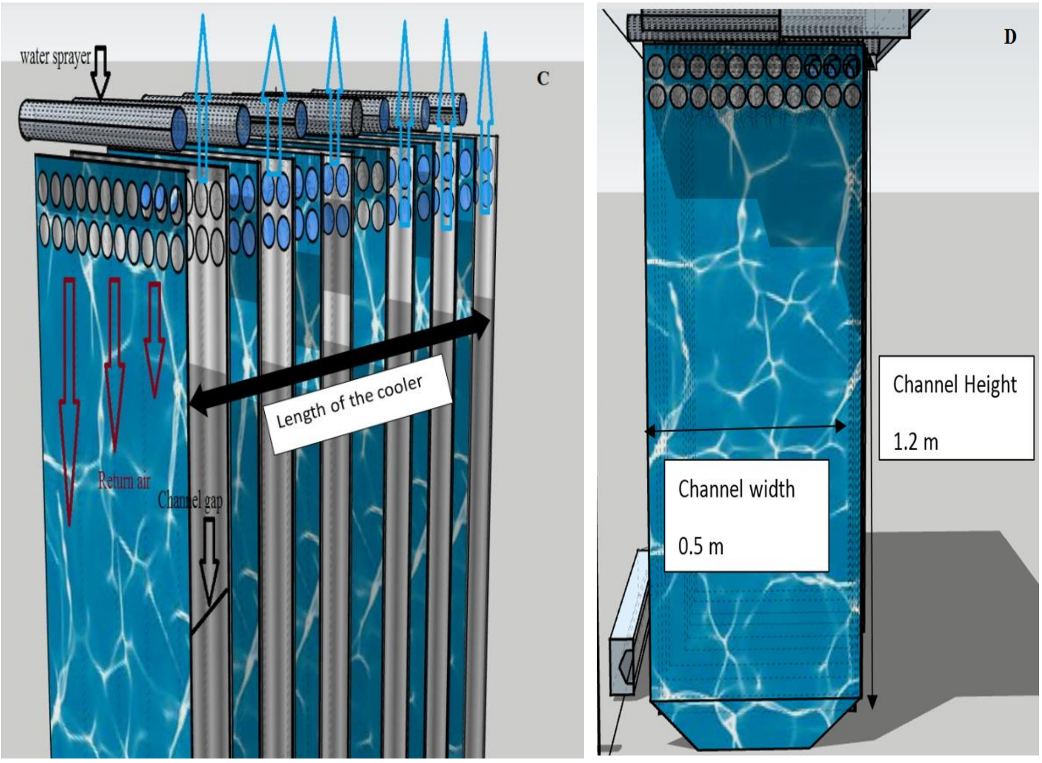


Figure 5-6: Heat Exchanger design and dimensions

5.6 Application of the Dew Point System

5.6.1 Case Study 1 (Ashti House)

The cooling load that was obtained from the building simulation with the applied building construction parameters was used to determine the required size of the heat exchanger to cover the building cooling and keep it within appropriate comfort levels.

Table 5-9: Dew point heat exchanger size analysis

Size	0-0.5 m	0.5-1 m	1-1.5 m	1.5-2 m	2-2.5 m	2.5-3 m	3-3.5 m	3.5-4.5 m
Total Covered hours of 4392 simulated	2291	3544	3999	4256	4348	4372	4384	4392
Extra hours for increase/0.5 m		1253	455	257	92	24	12	8
Percentage of cover %	52.16	28.53	10.36	5.85	2.09	0.55	0.27	0.18
Total percentage %	52.2 %	80.6 %	91 %	97 %	99 %	99.5 %	99.8 %	100%

In analysing the house baseline model for dew point cooling system heat and mass exchanger sizing data. Table 5-9 shows the coverage hours for different length of the heat exchanger. A heat exchanger size of up to 0.5m (0.5m x 0.5m x 1.2m) could cover up to 2291 hrs from a total of 4392 hours, a heat exchanger length of up to 1m length would cover another 1253 cooling required hours (3544 hours of total cover). A length of 1-1.5m would cover another 455 hours, 1.5-2 m gives an extra 257 hours cover, 2-2.5 m covers another 92 hours, 2.5-3 m covers 24 hours, 3-3.5 m covers another 12 hours, and sizes over 3.5 – 4.5 m covers the extreme sizes required in August when humidity is relatively high. The percentage to which the cooling load and sizes are covered is shown clearly in Figure 5-8 and Table 5-9**,** as the size of 3-3.5m will cover 99% of the entire year's cooling load. The remaining are for extreme times when the cooling load is very high, but the numbers of that extreme hours are only 20 hours of the extreme load that requires 3.5-4.5m long heat exchanger. This sizing of the dew point is for the baseline model house when there is no insulation or other improvements applied to the building parameters.

The maximum cooling load in the house was on July 21st when the ambient temperature was over 43^{o}C at noon and the humidity ration RH was 22% only, while there is a shift in load due to thermal mass in the building and the timing at which maximum cooling is required, as detailed in the previous chapter on cooling load. The scenario is different for the dew point cooler, as the cooling output of the unit is purely dependent on the ambient dry bulb temperature and humidity, especially in our case when the primary inlet air is 100% fresh (outside) air. As mentioned in the literature, drier air gives better results. In this work the maximum cooling was achieved when the air was very hot and dry, so for Kurdistan, this occurred in August as the ambient temperature was over 42 ^{o}C and the relative humidity RH% around 17%; consequently, the cooling output of the heat exchanger was at its highest.

However, the required maximum dew point size was found to be in mid-August due to the high humidity at this time of year, although cooling output was small compared to the maximum described in the previous paragraph. To cover a cooling load of 15 kW the units were required to have a unit size of 4.43 m in length, 1.2 m high and 0.5 m wide;

despite this load being only for one hour, to bring the internal temperature down to comfort levels, the required size has to be a length of 4.43m, Table 5-9 shows the percentage of each size required for the Ashti baseline house, where a size of 4.43 m is required for less than 8 hours out of 4392 hours of cooling. Hence, the cooling load and sizing combination together cannot be easily calculated, though having access to weather data and the hourly output of the system is of great help in terms of combining with the building load to calculate and estimate the best heat exchanger size.

5.6.1.1 The Baseline Model Dew Point Cooler Capacity

The optimum dimensions of the dew point cooler were previously selected. The only parameter that was left to be decided was the length of the cooler or the number of channels required to cover a particular building demand at particular times and weather conditions. The width of the cooler was set to 0.5 m, and the height was found to have the best output when at 1.2 m. Figure 5-7**,** shows the peak July ambient air conditions with the cooling output of 44 channels in the dew point cooler, whose maximum output reached 1.72 kW when the dry bulb temperature was 42.4^{o}C, and the humidity is as low as 21%. When it is very dry the capacity of the system is very high, the dryer air showing a better result for the dew point cooling and better cooling output, leading to the need for a smaller sized unit to cover a given building load. The shown result is for the hottest day of Erbil, which is normally known as the design day. The output could be used and generalized for similar areas and weather conditions. It also could be used to estimate the heat exchanger size, based on the known relative humidity and outdoor dry bulb temperature.

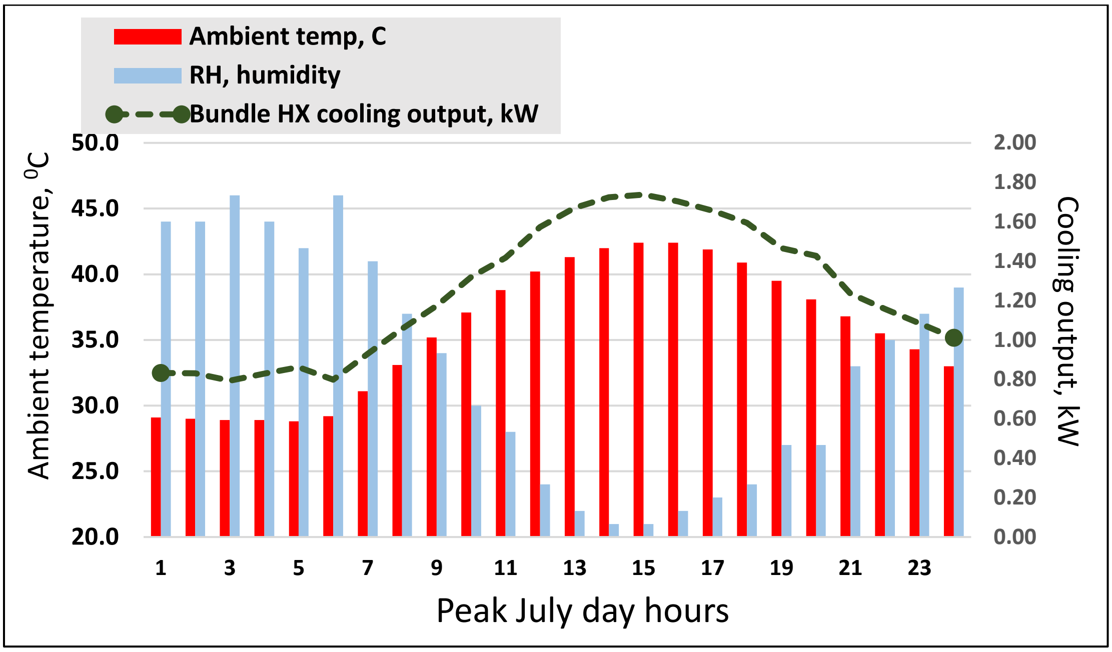


Figure 5-7: Ambient temperature and relative humidity and 44-channel dew point cooling output, in kW.

5.6.1.2 House Unit Cooling Capacity

For the Ashti house, for the hourly cooling load used to design the dew point cooler sizing the maximum number of heat exchanger packs required was 26.2. Each pack of channels is 17.65 cm thick and contains 44 wet and dry channels. This requires a unit of 4.308 m in length at peak load on the hottest day in July. Figure 5-8 shows the dew point cooler size required for the Ashti baseline model on a peak day in July. The cooler output is significantly affected by the ambient air conditions because of its use of 100% fresh air. For night-time cooling, which covers the two bedrooms, a system with a 1.20 m-long heat exchanger can cover the night load. At about 19:00, when most of the zones are cooled until 23:00, the size required to cover the load requires a system under 3 m long. At about 23:00, when all zones are cooled, for a short time at peak load the size of the cooler needed is as large as 3 m in length.

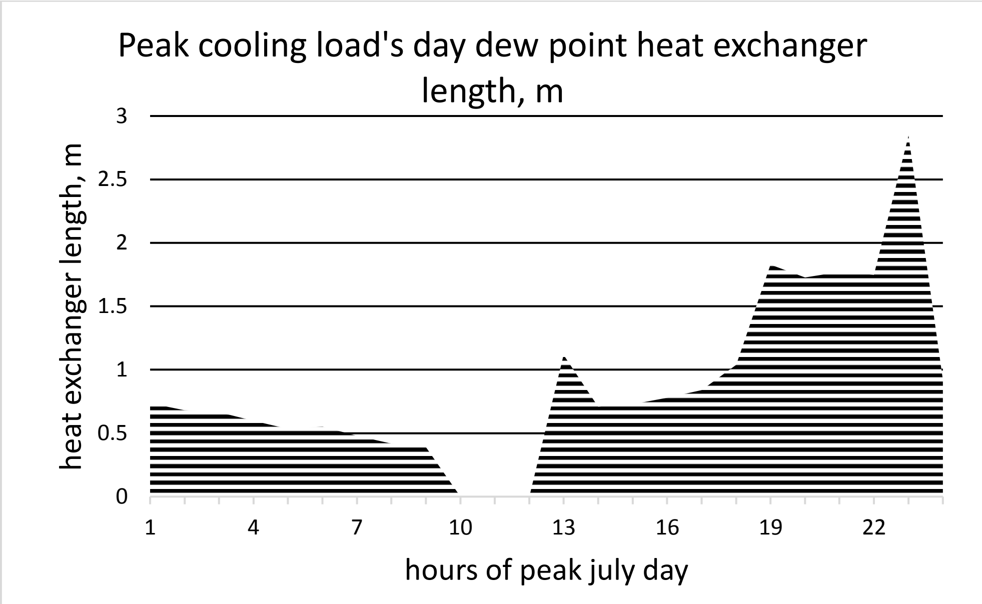


Figure 5-8: Peak July heat exchanger length required for the house unit.

5.6.1.3 Effect of Individual Parameters on Dew Point Size

When multiple parameters are applied to improve and reduce the cooling load, each parameter has shown its effects on the load and consequently, the size of the heat exchanger required. On the peak day, the effects of orientation have no obvious effect at all, it changed between 4.43 to 4.53 m for the East orientation, this is relatively very small, so it could be said that the orientations have neglected effect on the size. Glazing improvement, clear double-glazing or low emissivity windows with clear glazing did not show any reduction in the size of heat exchanger compared to the base model sizing. The use of clay blocks resulted in a reduction in cooler size thickness from 4.43m to 3.70m.

External wall insulation favourable affects size if applied to the building, where 3 cm – the optimal insulation thickness – will reduce the length required from 4.43 to 3.70 m, whilst the 4, 5 and 6 cm thick layers of insulation require a 3.82, 3.78 and 3.75 m cooler length, respectively. The suspended ceiling also has a favourable effect on the dew point heat exchanger, reducing the required length of the unit from 4.63 to 4.03 m. Although this length is affected by the hourly ambient external temperature and humidity as the heat exchanger's operation is based on the use of 100% fresh air, when humidity is low the output capacity is at its highest, which hugely affects the size of the dew point heat exchanger as well as the load.

5.6.1.4 Dew Point Cooling System Peak Time Sizing

The peak day for the cooling demand is normally used to design the cooler, 21st July is used because of the high ambient air temperature of almost 43°C. Appropriate sizing of the dew point indirect evaporative cooler was decided by interlocking the cooling load of the building as well as the ambient air conditions such as dry bulb temperature and relative humidity. The peak cooling output for the dew point indirect evaporative system was towards the middle to the end of August. If the ambient temperature was high and over 40°C and the outdoor air humidity RH% was low 16-20 % leads to an important point which is, the maximum cooling load of a building at a certain time and temperature does not imply the maximum sizing of dew point cooler heat exchanger at that particular time, especially when the hourly building load combined with the hourly output of the dew point heat exchanger system.

The maximum sizing for the dew point cooler turned out to be dictated by the conditions in mid-August, when the relative humidity was close to 60% and the temperature was over 31°C, combining the output cooling of the heat exchanger pack with the cooling load of the building gives an indication requirement for 25.11 packs of 17.65 cm thick dew point heat exchanger, this means a (4.43 m) long system. This maximum sizing is determined by the peak cooling required during the day when all the zones are cooled at the same time, although this does not happen in July when it is dry and hot. However, this maximum sizing of the heat exchanger occurs when the load is much lower than the peak hot day. Figure 5-9 shows the effects of the parameters on the maximum sizing of the heat exchanger in August in comparison with the baseline model size. The suspended ceiling has a positive effect as it brings the size down to as low as 4.03 m. Figure 5-9 shows the effects of each of the individual parameters, including the orientations concerning the base case model.

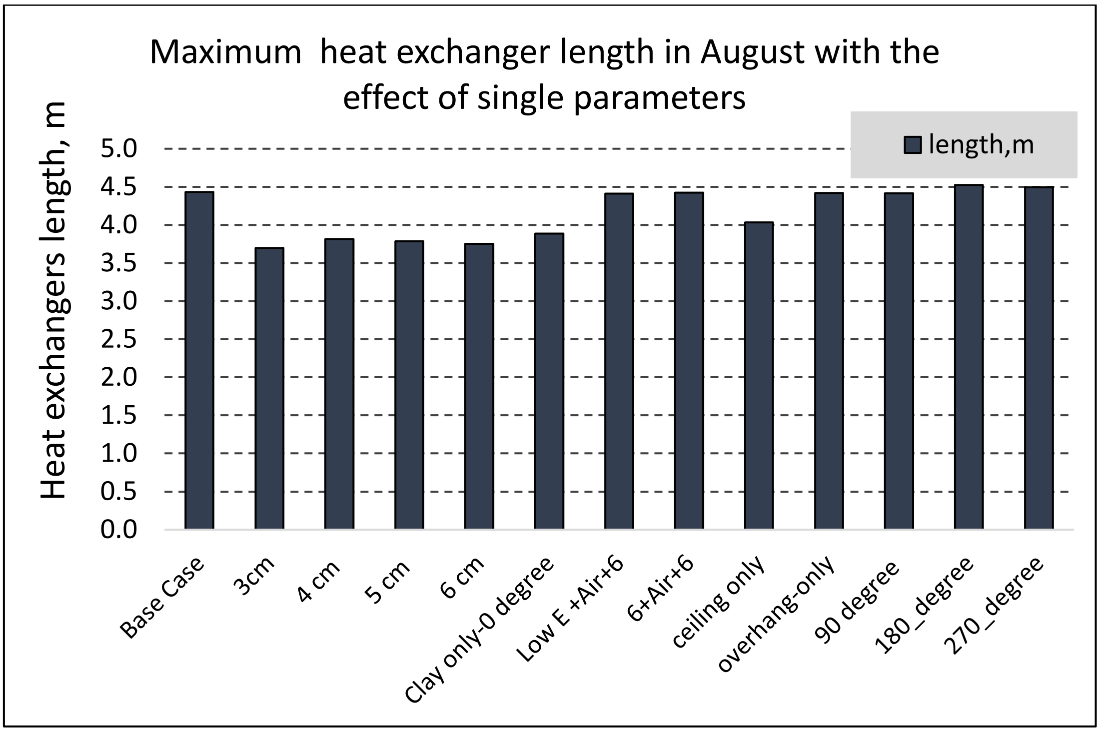


Figure 5-9: Maximum size required for the house with the effect of parameters on size-reduction

5.6.1.5 Maximum and Optimum Parameters for the Dew Point Heat Exchanger Length and Size

The maximum reduction in cooling load was obtained using the following parameters (clay blocks, low emissivity glazing, 6 cm insulations, suspended ceiling, and overhangs) these parameters together reduced the load from 17.44 kW to 11 kW. In the meantime, the optimum parameters for the case were the use of (clay blocks, and 3 cm insulations with the suspended ceiling) and brought the maximum cooling load down to 12.1 kW. The cooling load reduction for the optimum and the maximum (12.1 and 11 kW) for the hottest day in July did not cause the maximum sizing as the dew point cooling system has a very good output when the climate is hot and dry. The peak sizing of the dew point cooler was found to be in August when the ambient air was hot and slightly higher in humidity, which reduces the output of the system and requires a bigger size to cover the load. In this case, the peak sizing of the cooler with the parameter of the optimum and all intervention parameters recording a length of 3.17 m (18 packs) and 2.9m (16.5 packs) respectively.

Again, the baseline model, optimum and the maximum saving parameters were compared together in terms of sizing to design the heat exchanger for the dew point cooler to cover the house cooling requirement. The maximum reduction in size for the dew point cooler was from the baseline 4.46 m long to 2.9 m with all parameters, while the optimum reduced the heat exchanger to 3.17 m, which represented only a 0.26 m difference, this difference between applying all parameters and the optimum choice is only 1.5 pack of heat exchanger as shown in Figure 5-10. There is no significant effect on the cost or the water consumption if designed using this method.

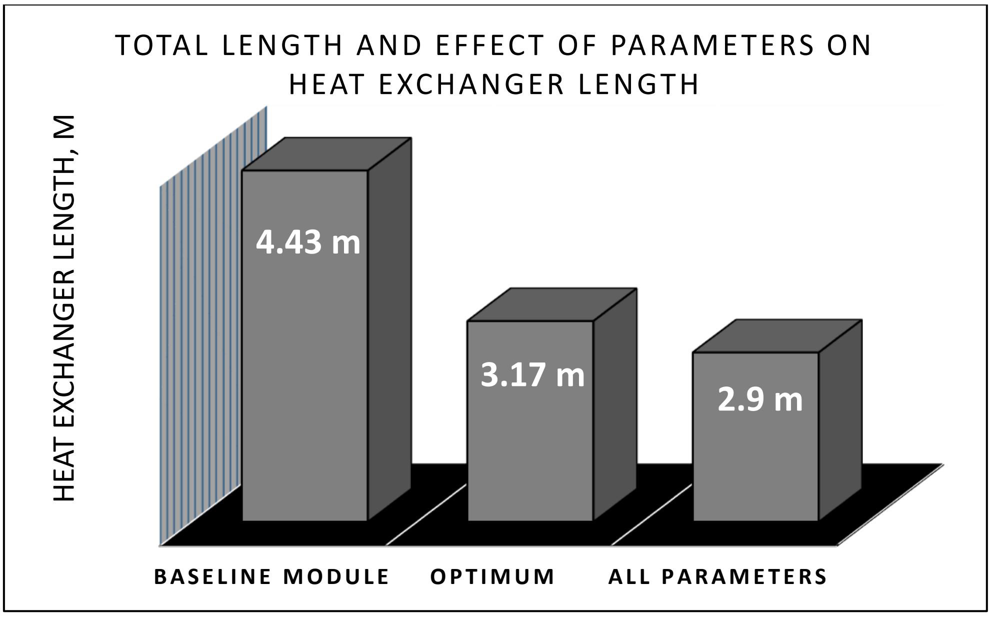


Figure 5-10: Maximum and optimum sizing of the dew point cooler compared with the baseline in August

5.6.1.6 July and August Peak Maxima and Average Sizing and Coverages

As illustrated earlier in some detail, the maximum load does not imply the maximum size of the indirect dew point evaporative heat exchanger, because the size required to cover the entire load of the building is controlled by the input air, humidity and ambient temperature. Hence, the maximum size is not a direct function of maximum cooling load alone, but also a function of high humidity ratio outside the building at night time, as during the day time the humidity ratio is relatively low comparing to night time. This means that this system is more active during the daytime rather than night times; when the air is hot and dry, the system performs much more efficiently.

Figure 5-11 shows the results of maximum size and the daily averaged peak size from the beginning of July until the end of August. The shown figure covers all three cases, namely the baseline, optimum and all parameters. It may be noticed that the baseline model size would benefit from this and the length reduces from 4.43 to 2.63 m, the optimum sizing reduces from 3.17 to 1.91 m long, and the maximum parameters' heat exchanger length would reduce to 1.74 m. This method would reduce the baseline heat exchanger by 1.8 meters, the optimum by 1.26 m, and all parameters application reduced the heat exchanger by 1.17 m in length.

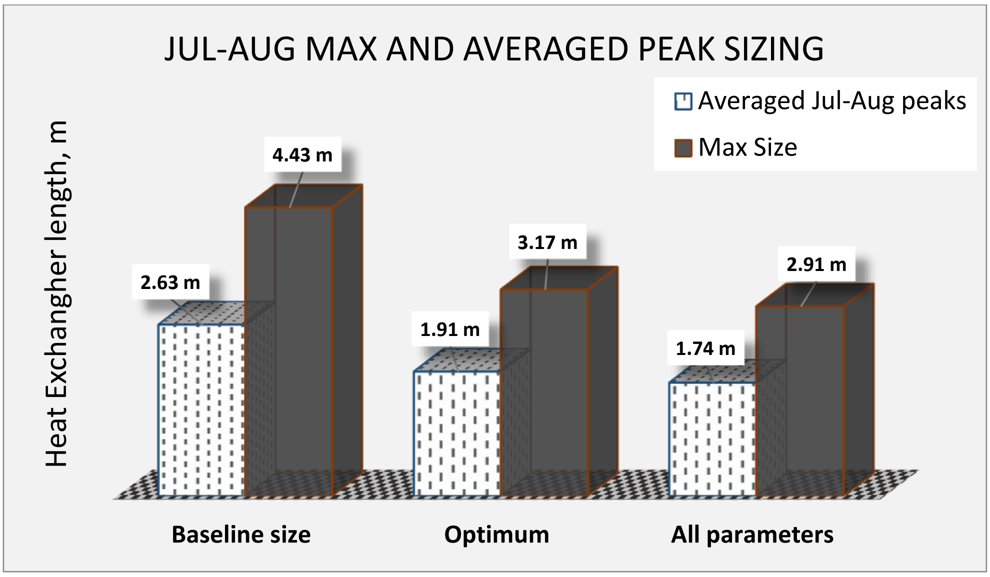


Figure 5-11: Peak sizing and averaged daily peak sizes from July to August dew point cooler sizing of the baseline, optimum and with all parameter.

Figure 5-12 covers most of the cooling required hours. The sizing method can cover more than 99.3 % of the required cooling hours in the house, but there are only 41 hours during which this size cannot deliver the requirements of the house.

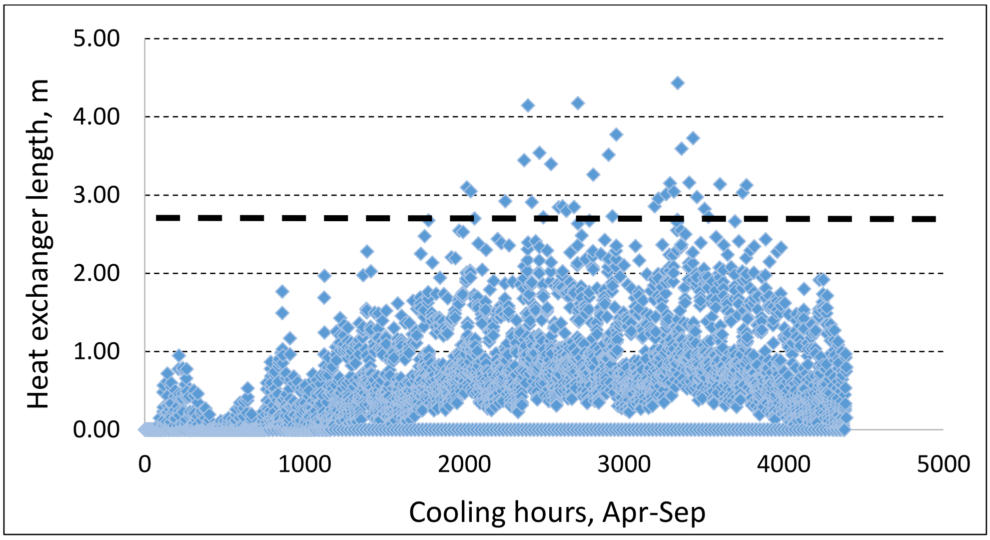


Figure 5-12: Averaged peak sizing method and covered cooling hours.

The size could not cover the unmet hours in the building when the loads are at a peak, the ambient temperature is generally over 30°C, and the ambient relative humidity is high. In more technical words, the temperature cannot evaporate the water in the wet channels sufficiently to cool the air enough to cover the cooling load.

5.6.1.7 Water Consumption Rate

In the selection of model parameters for the simulation, it was decided that the priority was for the cooling output rather than water consumption, as water is available and does not cause significant issues. For the selected size, the evaporation rate of the water varies depending on the air humidity. On the hottest day, which is 22nd July, the average water consumption for the baseline model is 41.12 l/hr and a total of 863.4 l/day while for the optimum unit size the consumption of water is 29.44 l/hr and 618.3 l/day. The lowest consumption was when the building has all parameters applied and the load in the building is at its lowest, where the average water evaporation rate is around 27 l/hr and the daily consumption rate around 567 litres. The water evaporation rate is strongly dependent on the size of the dew point cooler. However, for each location, the system applied the evaporation rate of water per output l/hr/kW of cooling is strongly dependent on weather condition.

Table 5-10: Water consumption rates for different heat exchanger sizes and effects of building parameters

	Baseline	Optimum	**All parameters**
Number of Packs	25.1	18	16.5
Heat exchanger length, m	4.43	3.17	2.9
Volume heat exchanger, m3	2.66	1.91	1.75
Total water, litre	98,913.5	72,932.6	67,238.2
l/hr (annual)	30.93	22.64	20.73
Jul-Aug ,l /hr	36.21	26.5	24.34
Hourly consumption of peak July day 21hr operation/day	41.12	29.44	27.02
peak July day water consumption, litre	863.4 litre	618.3	567.4

Table 5-10 shows the water evaporation rates for each sizing scenario when adopted for the house unit. It also analyses the average evaporation on the hottest day and hottest months (July-August). The water consumption by the baseline model heat exchanger is quite high, at 41.12 l/hr, because of the unit size of the heat exchanger. The averaged sizing method is very effective for buildings even without additions or improvements and will reduce the annual water consumption to 58,700 litres.

The optimum parameters will save annually 26 m^3 water, which is a considerable amount of water. In the meantime, if all parameters are applied to the building the size of the dew point system, as well as the water consumption, can be reduced. The water evaporation for a 2.91 x 1.2 x 0.5 m cooler size will reduce the annual water consumption to 67,238 litres, which means an average water consumption of 20.73 l/hr. Applying all proposed interventions to the building and the cooling system would save about 32 m^3 of water annually, which enables the new cooling system to be easily applied to the locations without incurring high operational costs.

5.6.2 Case Study 2 (Heja Flats) HMX Sizing Units

In chapter 4, the details of the cooling loads and capacities for each unit were examined and analysed in detail, as were the building parameters and orientations. It was found that some parameters are very effective at allowing for energy savings and reducing the cooling load in the flat, such as clay blocks, insulation, and low emissivity glazing. On the other hand, some other parameters have absolutely no effect on the energy and load, so adding such parameters would not benefit the building in any way.

In this section, the same flat baseline loads will be used to determine and size the dew point heat exchanger, and the optimum cooling load parameters, as decided in the cooling load chapter, allow the examination and analysis of the sizing of the unit, as well as allowing the rate of water consumption and saving estimates to be determined. The same process will be followed for all individual flats and all the flats on the floor simultaneously.

5.6.2.1 Flat A Dew Point Heat Exchanger

The same heat exchanger pack with 44 (dry/wet) channels and its outputs was applied to the hourly cooling load for the flat A baseline model. Although the design and peak temperature day was in late July, when the ambient temperature is very high at 43 °C, the peak day load in flat A was 9.44 kW but the maximum cooling load showed in the previous chapter for this flat A was in mid-August, when it rose to 9.73 kW, when the ambient temperature was 41.5^{o}C. Figure 5-13 shows the sizing required for 24 hours in hot August day, although this is the peak load day for flat A, but it is not the peak sizing, the peak sizing is decided by the weather conditions as the system works on 100% fresh air from the ambient.

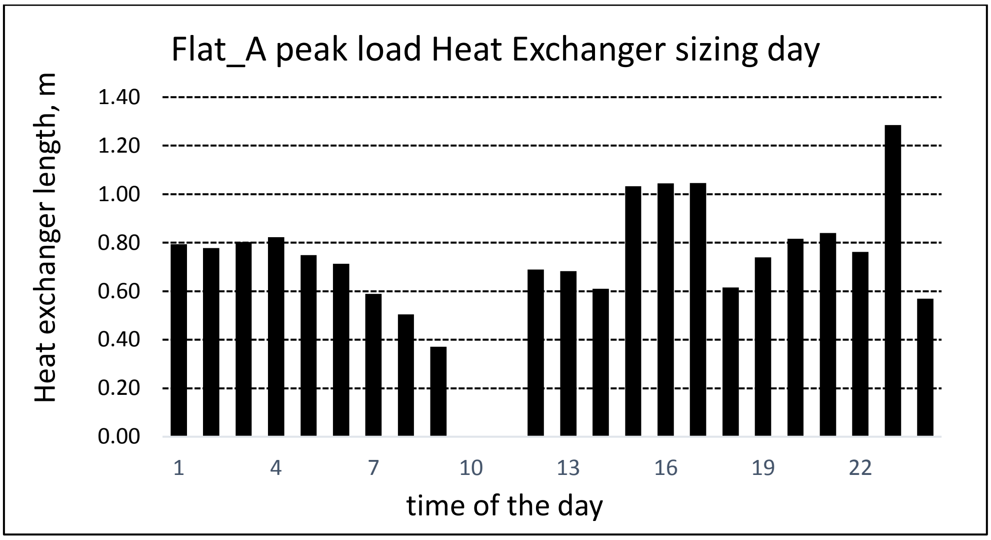


Figure 5-13: Flat A peak load day dew point sizing

The maximum sizing for flat A was found to be in mid-August when the ambient temperature is relatively hot and with high relative humidity, which reduced the effectiveness of the dew point system and thus resulted in the sizing required to deliver the required cooling being as high as 2.44 metres long. The pattern of the cooling load, which has a maximum between 14:00-17:00 is not the same for the heat exchanger sizing but is, nevertheless, also controlled by the ambient temperature and humidity.

5.6.2.2 Effects of Parameters on Flat A Heat Exchanger Sizing

Following the analysis of the effect of parameters on flat A, it was deduced that the maximum saving was by adding (clay blocks, 6 cm insulations, low emissivity glazing and overhang from outside), but the optimum parameters for flat A required (clay blocks, 3 cm thick insulation, and low emissivity glazing); overhangs and a suspended ceiling didn't change the load to any appreciable degree. Figure 5-14 below shows the effects of three cases compared together, which all covering the required load for the flat A, where the saving in size is large when using the optimum parameters, representing a saving of about 58 cm in length, while with all parameters maximized there is not very much difference, at 66 cm in length.

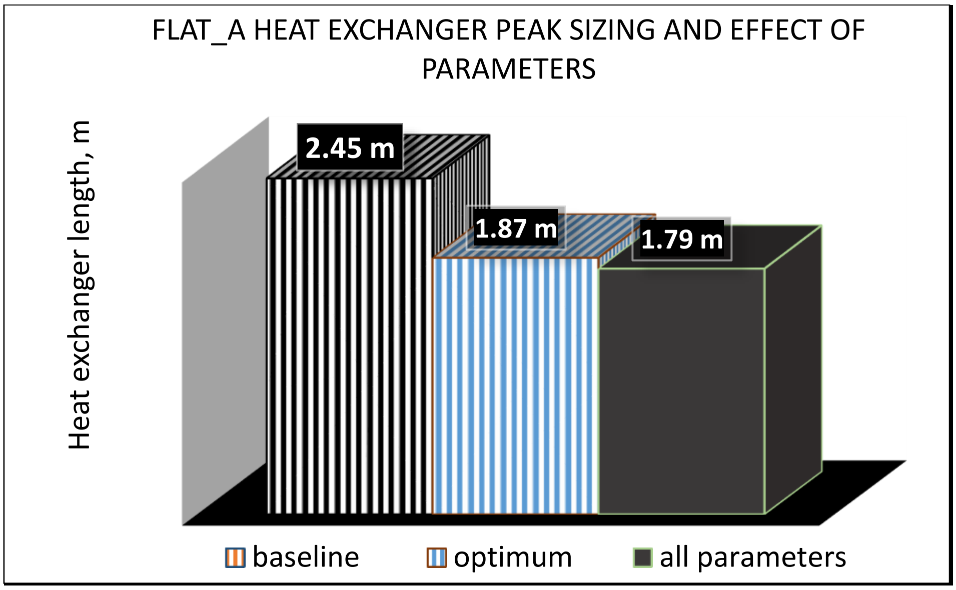


Figure 5-14: Effect of parameters on flat A dew point heat exchanger sizing

5.6.2.3 Water Consumption for Flat A

As described earlier in the simulation parameters, the dew point system water consumption is dependent on the ambient weather conditions as well as its physical parameters and velocity, where this is system is designed to achieve best cooling output and is less reliant on the water evaporation rate as the priority was given to the cooling. The water consumption for the above three cases is shown in Table 5-11, where the baseline model contains almost 14 packs of channels, the optimum 10.6 packs and with all parameters becomes10.16 packs which means a reduction of 3.7 packs of channels.

Table 5-11: Flat A dew point sizing and water consumption, with the effect of parameters

	Baseline model	Optimum	All parameter
Number of packs	13.8	10.6	10.2
Length, m	2.45	1.87	1.79
Water l/season	61898	47349	45341
Total water, m3	61.90	47.35	45.34
Average summer day Jul-Aug l/hr	20.69	15.83	15.16

It could be noticed from Table 5-11 that the water evaporation between the optimum and maximised parameters is not particularly different at annually 2.01 m^3 water, which is very small and of negligible cost, while in contrast, the difference in consumption between the optimum and the baseline model is quite noticeable at 14.5 m^3 water. This shows that selecting the optimum gives the right sizing and thus represents the correct selection from among the parameters.

5.6.2.4 Effects of Parameters on Flat B Heat Exchanger Sizing

Flat B has been analysed for the dew point coolers heat exchanger. The maximum requirement and the peak load were found to be on the 22nd July, which is known to be very hot, although this peak load does not occur at the peak temperature hour. The load for Flat B was 6.44 kW and, when applying the parameters to bring the load and the energy consumption down, the optimum parameter reduced the load to 5.13 kW, and with all parameters included the load was reduced to 5 kW only, which is a very small amount.

When the load is high because of the high ambient temperature and low humidity, the heat exchanger gives its best output. The hourly dew point cooler's outputs from the heat exchanger pack (44 channels), has been used to size the heat exchanger of the dew point cooler for Flat B. For the hottest hour and day, the heat exchanger unit is relatively small. A unit of 4.3 packs, or 0.75 m for the baseline model, for the optimum is 3.39 packs and 3.31 for all parameters (0.6 and 0.58 m), total length, this all because of the effectiveness of the system at hot and dry times as shown in Figure 5-15.

The maximum sizing for the baseline was found to occur on 1st August when the cooling load was 5.26 kW lower than at peak, indicating a requirement of 8.7 packs of heat exchangers (1.53 m), which was when the heat exchanger gives a 0.604 kW cooling output. For the optimum and all parameters, the heat exchanger is reduced to 7.18 and 7.03 packs, or 1.267 and 1.24 metres in length, respectively. This happens when the ambient temperatures are not that high at 29^oC, but humidity is at 57%.

The maximum sizing for the optimum and all parameters when applied to Flat B is 1.73 and 1.72 m, this occurs when the cooling load is very small, and there is not any solar irradiation or high ambient temperature, and cooling loads are 2.2 and 2.19 kW in May.

The original baseline load was 1.9 kW; this is before applying the insulations to the building as it kept the internal heat inside the flat and did not fade through the walls. In this case, when cooling was required, and the external temperature is low with high humidity as 20.3°C and 79%, the low ambient temperature cannot evaporate the high humid external air, for that reason, the size of the exchanger has to be bigger to cover the required cooling load. This is the constraint point of the dew point cooler, highly affected by the humidity ratio of the external air. These two cases cannot be compared with the peak sizes to assess the effects of the building parameters as they do not occur at the same time.

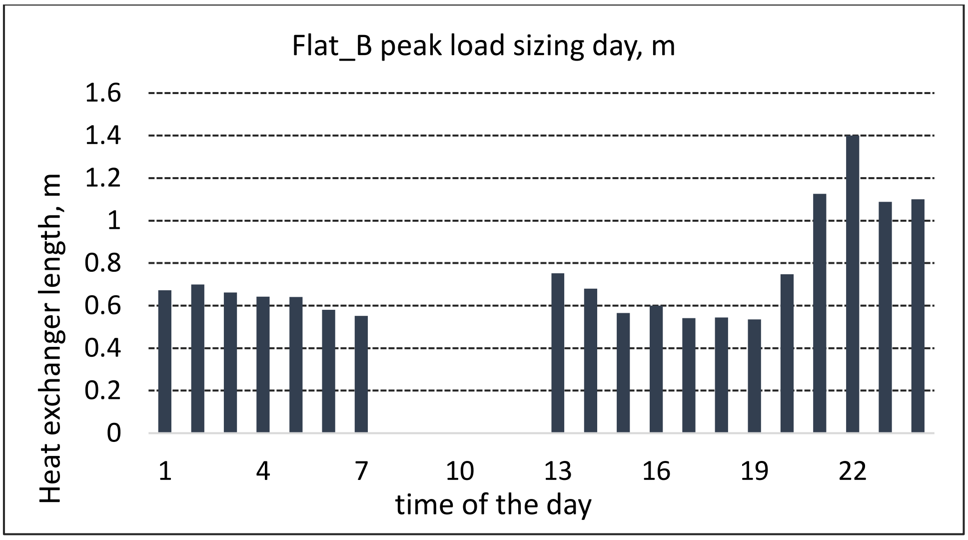


Figure 5-15: Flat B peak load day heat exchanger sizing

Figure 5-16 shows the effects of two groups of parameters on the heat exchangers length. The length is close to each other because, 1) the cooling output of the heat exchanger is high at the time which squeezed the difference, 2) Flat load is small, and hence the difference is hard to be seen. Although there is about 30 cm difference which almost makes two packs of heat exchangers for all parameters and it is slightly less for the optimum. It also could be seen the difference between the optimum and all parameters is almost none, which tells the selected parameters for the optimum are adequate

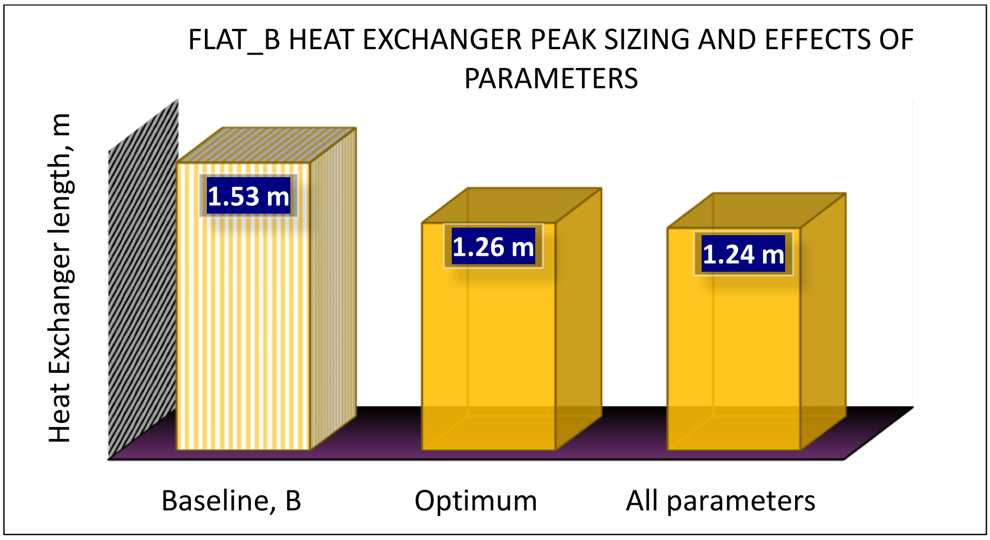


Figure 5-16: Flat B, effects of baseline and parameters on heat exchanger sizing on the peak load day

For the complexity of the flat B sizing, Figure 5-17 shows August's capacity requirements for Flat B and the effects of the optimum parameters on the heat exchanger length.

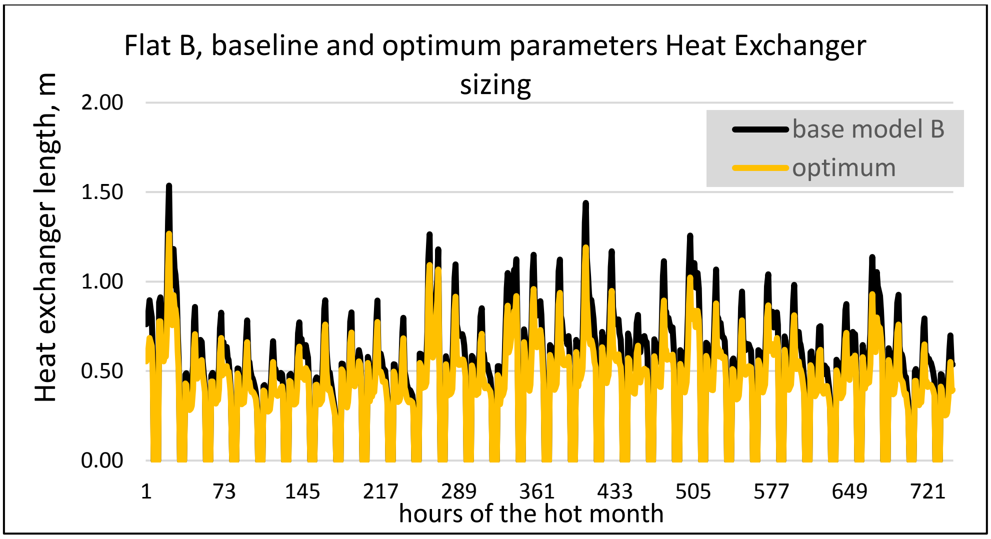


Figure 5-17: August heat exchanger sizing for the base model and the effects of optimum parameters on length.

5.6.2.5 Water Consumption for Flat B

In consideration of the worst-case scenario for the sizing to cover the building load completely, the following table was not designed according to the peak load day, but according the maximum sizing to the cover the loads entirely. The water consumption rate for the maximum sizing was calculated, this means the water consumption cannot go over this value at all in case if this data used for any other estimation or engineering purposes, this is because of the heat exchanger was designed with 3m/s air velocity. There is hardly any difference between the effects of the application of the optimum and all parameters, as illustrated in Table 5-12.

Table 5-12: Flat B dew point sizing and water consumption with the effects of parameters on each

	Baseline model	Optimum	All parameter
Number of packs	8.7	7.2	7.1
Length, m	1.53	1.26	1.24
l/season	33315	27463	26889
Total water, m3	33.32	27.46	26.89
Average summer day Jul-Aug l/hr	12.99	10.71	10.49
Annual average water, l/hr	10.27	8.47	8.29

5.6.2.6 Effects of Parameters on Flat C Heat Exchanger Sizing

Flat C is a medium-sized family residential unit housing four occupants. The peak load in the flat was on the 22nd July when the ambient temperature was relatively high, and the time of the main cooling requirement was towards the evening. Cooling usage schedules have a considerable impact on sizing the dew point heat exchanger, especially when 100% fresh air from outside is used; similar to direct evaporative cooling systems, the weather conditions (ambient air temperature and humidity) when the cooling is required has a big impact on the capacity and sizing of the cooler.

Figure 5-18 shows the peak day sizing profile of the heat exchanger for the flat C base model according the peak load obtained for the flat. The optimum and all parameters effects have been applied to the flat to examine their effects on the heat exchanger sizing for this particular day. The maximum effect on dew point exchanger for this day is in the mid-day timing, but the family members are not using the cooling system otherwise, the output of the system is very high, it is approximately 1.6 kW cooling per pack of heat exchanger at 14:00.

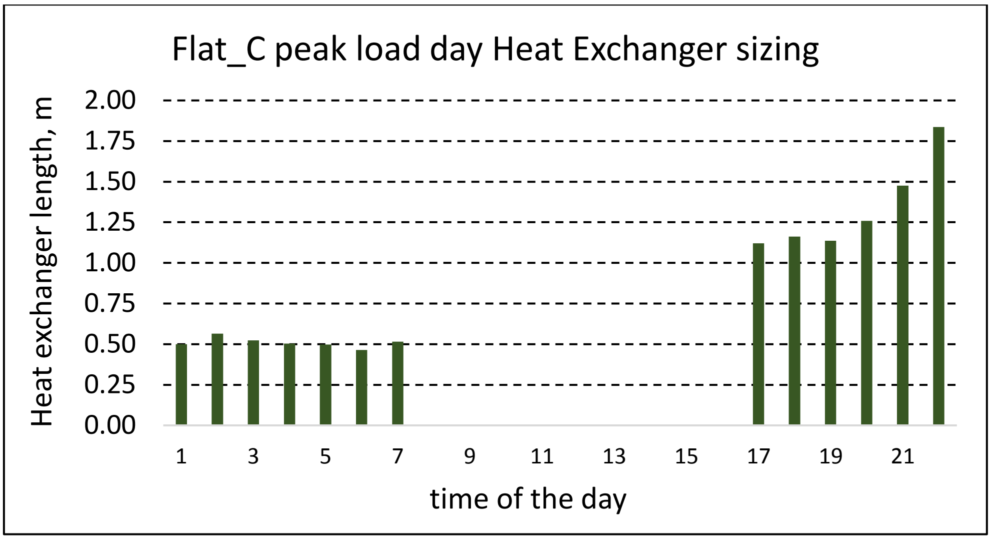


Figure 5-18: Flat C peak day heat exchanger sizing

The peak sizing of the dew point heat exchanger is on the same day as the peak load, though not the same time. The peak sizing for the Flat C baseline model was 10.4 packs or a 1.83 m length of heat exchangers at 22:00 when the ambient temperature was 33.7^{o}C, and the humidity was 51%. After applying the insulation and other parameters as discussed earlier, the optimum unit parameter reduced the packs to 7.2 (1.27 m) which the application of all parameters reduced further to 6.8 packs (1.2 m). Figure 5-19 shows the differences in three different sizes, clearly showing the optimum effects on the baseline model for Flat C.

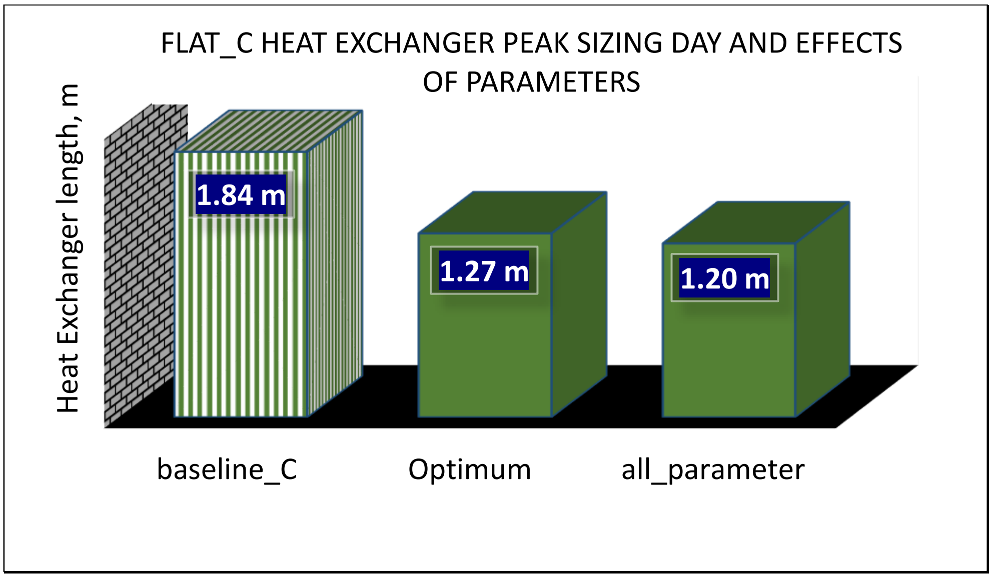


Figure 5-19: Peak sizing for Flat C heat exchanger length and the effects of the various parameters

It can be noticed that the optimum parameters reduced the heat exchanger size by almost 57 cm or 3.25 packs, while the all parameters were considerably different to the optimum, reducing the length by only 7 cm, or less than half of heat exchanger pack size.

5.6.2.7 Water Consumption for Flat C

The peak sizes selected for Flat C, including the optimum and the all parameters applied, used 10.4, 7.2 and 6.8 packs of heat exchangers to cover the hourly load in Flat C. Table 5-13 shows the rate of evaporation of water when the sizing unit was used in addition to the savings generated if the building is updated.

Table 5-13: Flat C, dew point sizing and water consumption and the effects of parameters

	Baseline	**Optimum**	**All parameter**
Number of packs	10.4	7.5	7.2
Length, m	1.84	1.27	1.2
l/season	20615	14272	13479
Annual water consumption, m3	20.62	14.27	13.48
Average peak day, l/hr	15.29	10.59	10.00
Volume of HX m^3	1.104	0.76	0.72
Average l/day	11.23	7.77	7.34

The number of heat exchangers, which is decided by the load and load reduction through the parameters applied to the building, would affect the water evaporation rate considerably. Hence, the rate of water evaporation is proportional to the number of heat exchangers used in the dew point cooler Flat D Dew Point Heat Exchanger Sizing.

Flat D, in a similar manner to the other flats, was examined in terms of appropriate dew point exchanger sizing. The second half of July is hottest in Erbil when the temperature rises to over 43°C, but the maximum load for this flat was found to be during the second half of August. That peak load has been used to design the heat exchanger unit to bring the temperature down to 25°C.

For the baseline model for Flat D, the number of heat exchanger packs required was found to be 5.48, equal to a length of 0.97 m, was found to be the maximum the flat requires. Although the flat's load is high (8.58 kW), the output of the heat exchanger is good due to the high ambient temperatures and low humidity (40°C and 24%). Figure 5-20 shows a 24-hour pattern for Flat D's peak day sizing. The peak load does not imply the peak sizing for the heat exchanger. The peak sizing of the heat exchanger was at the beginning of September when the temperature was moderate, and the relative humidity was high at over 63 %. The heat exchanger required 9.45 packs (1.67 m) for only 4.62 kW because the heat exchanger output is as little as 0.489 kW/pack.

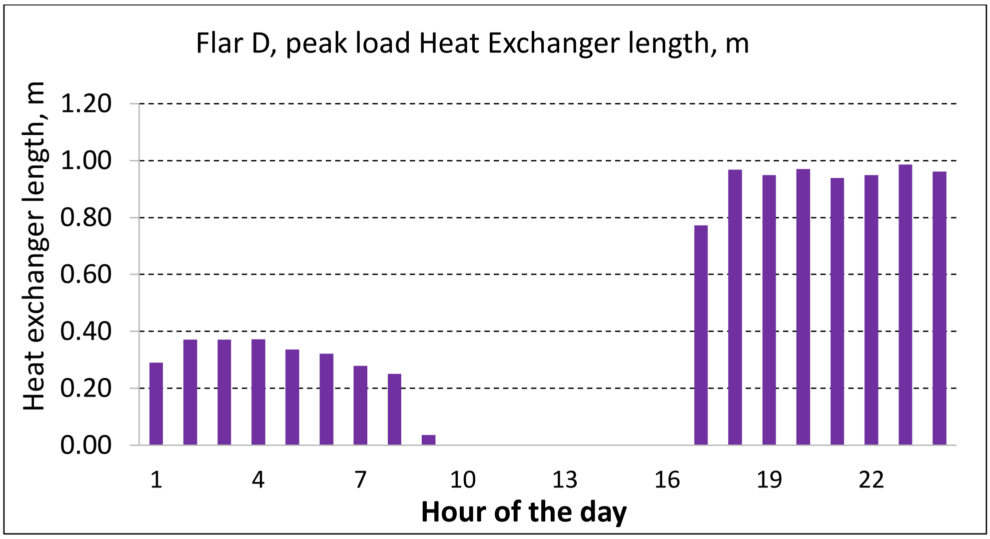


Figure 5-20: Flat D peak load day HMX sizing.

5.6.2.8 Effect of Parameters on flat D Heat Exchanger Sizing

The same parameters that were applied to the other flats were used in the case of Flat D to examine the effects of building construction updates on the heat exchanger's sizing. For the maximum sizing hour, which is in September, the parameters reduced the number of heat exchanger packs required from 9.45 (1.67 m) to 7 packs (1.23 m) with the optimum parameters, and which were found to reduce further to 6.39 packs (1.13 m) if all parameters were applied; this was less than one pack's difference compared to the optimum Figure 5-21, Shows the comparison of maximum sizing of the heat exchanger for flat D, and the effects of optimum and all parameters on the heat exchanger length, this is not falling in the peak cooling load day.

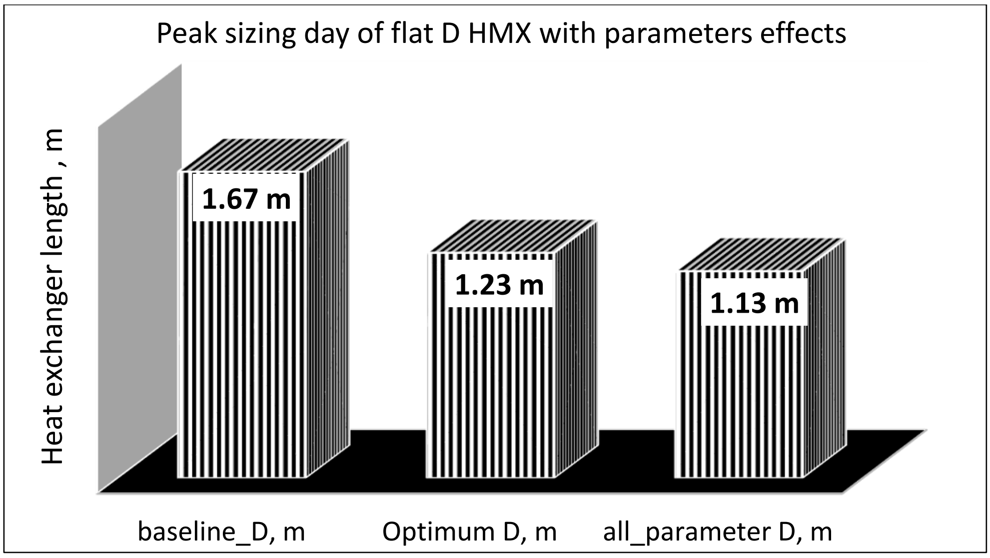


Figure 5-21: Peak sizing of Flat D heat exchanger length and effect of parameters

5.6.2.9 Water Consumption for Flat D

Water consumption was calculated for the Flat D, where the consumption or evaporation of water is not as large as other flats because this flat occupant has two days off where cooling is not used, which consequently affects the water consumption and cooling power.

Table 5-14 shows the annual consumption for the baseline model for the Flat D heat exchanger packs required in the building as well as the rate of water consumption during the cooling season and at peak time.

Table 5-14: Flat D, dew point sizing and water consumption with the effects of parameters

Water consumption Flat D	Baseline	Optimum,	All_ parameter
Number of packs	9.5	7	6.4
Length, m	1.67	1.23	1.13
Average annual	9.97	7.37	6.74
m^3	18.12	13.40	12.25
Average peak day, l/hr	14.32	10.59	9.68
Volume of HX m^3	1.002	0.738	0.678
Total, l	18,118	13,401	12,247

The water consumption for the two sizing's, using baseline and optimum parameters is different, while the difference between the optimum parameters sizing and all parameters are not particularly different, which again indicates that the choice of best effective parameters has been made. The importance of reducing the number of heat exchanger packs in this method is to save water and power.

5.6.2.10 Total Floor Flats Dew Point Heat Exchanger Sizing

Heja flats consist of four floors, though only the first floor is examined in this study. Data for the entire floor was studied and analysed to determine the sizing of the heat exchanger and water consumption. The hourly total cooling load that resulted from the simulation has been used, where the maximum floor load was found to occur on the 22nd July and 19th August, with each days' cooling load reaching 30.34 and 30.87 kW, respectively, when the ambient temperature was high, reaching over 40^{o}C at 17:00. The effects of the parameters on cooling load were obvious in the building, where the all parameters load was 21.37 kW, and the optimum parameter load was 22.45 kW. It should be noted that increasing the insulation from 3 to 4 cm in thickness with all other parameters otherwise held the same reduced the maximum load to 22.22 kW; although this represents a reduction, it is not a valuable difference and one which will not affect the sizing of the dew point heat exchanger.

The dew point heat exchanger was found to require 20 packs for both of these extremely hot days as there was only a very slight difference in humidity, 26% and 23%; for the optimum parameters, the number of packs required was 13.85, whilst for all parameters applications – when the insulation doubled and added with overhangs, the pack number was found to be 13.11, which is only three-quarters of a pack for the entire floor's flats.

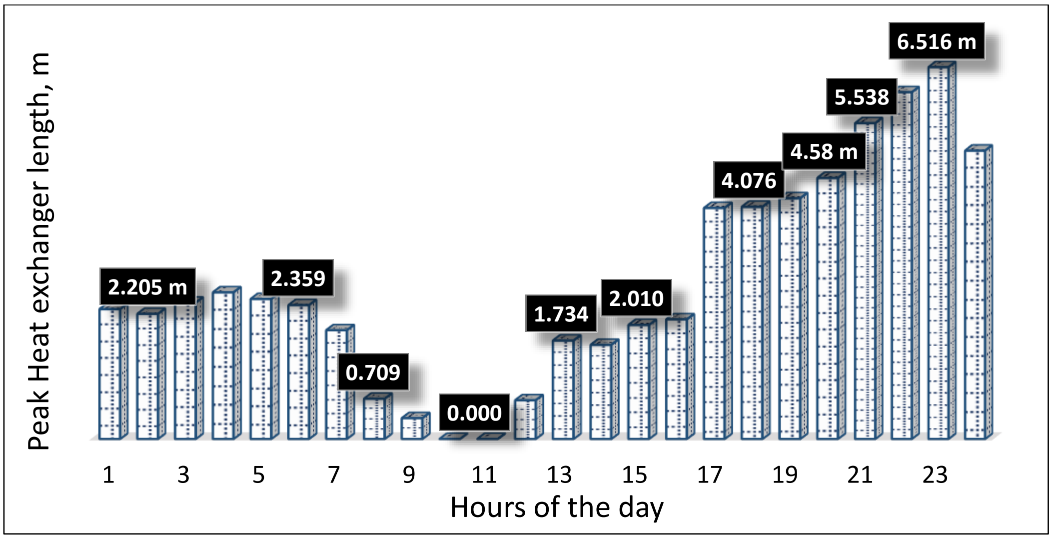


Figure 5-22: Peak of combined flat heat exchanger sizing

The maximum heat exchanger sizing for the baseline was determined from night-time requirements of July and August when the ambient humidity was high, at 53% and 60%, respectively, at about 23:00. The peak sizing for the entire floor of flats without any additions was 36.92 packs (6.51 m), as shown in Figure 5-22.

5.6.2.11 Effects of Parameters on Total Flat Peak Sizing Heat Exchanger

Using optimum parameters, the pack number decreased to 27.86 (4.91 m) while for all parameters the number of heat exchanger packs reduced to 26.48 (4.67 m) which is only a 1.3 pack reduction, as shown in the first row of Table 5-15. Although this is not the peak sizing of the optimum and all parameters, the peak size was found to be in May, with the same case conditions as Flat B, when the internal load is slightly increased and the ambient humidity is very high, at 79%. Table 5-15 reports the sizing of each of this times as discussed, where the baseline peak sizing has been selected to size the heat exchanger because the two cases of optimum application's sizing were very close in terms of pack numbers (baseline optimum and maximum optimum packs).

Table 5-15: Different sizing of the entire floor of flats due to parameters and weather conditions

Number of Packs based on:	Total pack	tot opt pack	**pack 4 cm**	**Tot all pack**
By: baseline peak sizing (Aug)	36.9	27.9	27.5	26.5
By: maximum opt sizing hottest day (Jul)	20.00	13.9	13.7	13.1
By: max of optimum packs (May)	25.2	28.3	28.6	27.2
By: peak baseline cooling load day (Aug)	19	13.8	13.7	13.5

To determine the actual size required for the entire floor of flats. The selection between the maximum size day and peak cooling load day sizing methods should favour size-reduction regarding the baseline's peak sizing, though this is if the parameters applied and the sizing is very close to the maximum optimum parameters, as shown in Table 5-15. Hence, the results for the entire floor's heat exchanger sizing would be as shown in Figure 5-23.

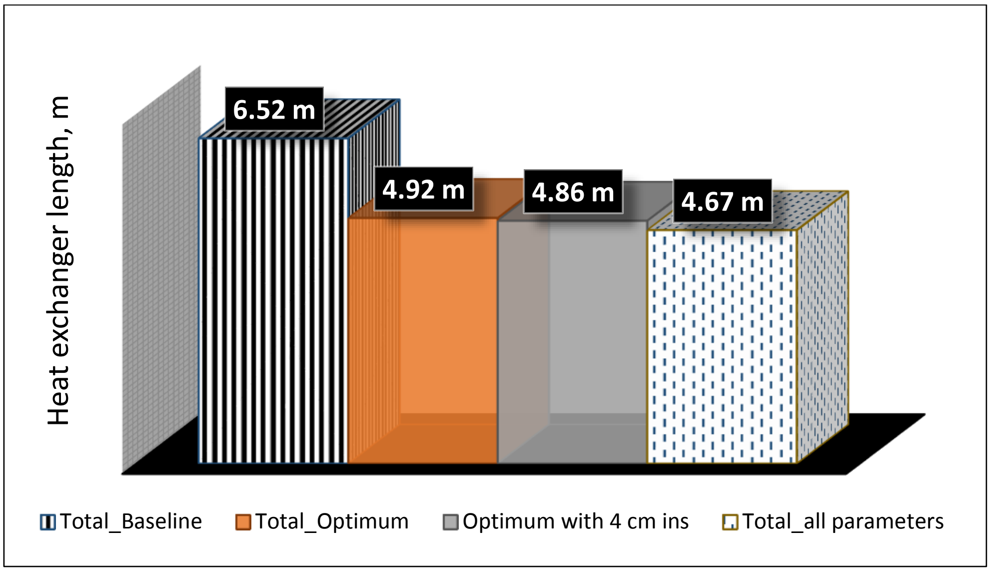


Figure 5-23: Entire floor of flats' dew point sizing and effects of parameters on length

Figure 5-24 shows the optimum heat exchanger sizing length, where the greatest saving was in the period covering July-August, as the dew point heat exchanger operates at its highest output when the ambient air is hot and dry.

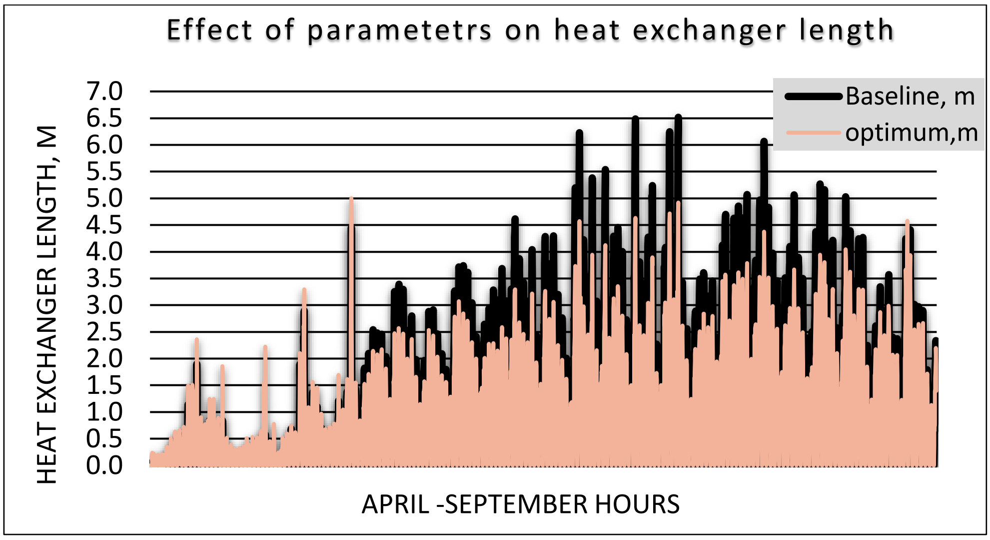


Figure 5-24: Effects of parameters on heat exchanger length in metres

5.6.2.12 Water Consumption for Combined Flats

According to the sizing of the baseline, the optimum and all parameters for the entire floor of flats, the total annual water consumption and average hourly consumption are reported in Table 5-16.

Table 5-16: Total first-floor sizing and effects of optimum parameters on water consumption

	Total baseline	Total optimum	Total all parameters
Number of packs	36.9	27.9	26.5
Length, m	6.51	4.92	4.67
Average l/hr	45.02	33.98	32.29
Jul-August average l/hr	55.08	41.56	39.51
Total consumption, l	160,454	121,089	115,091
Water, m^3	160.45	121.08	115.09
HX volume m^3	3.906	2.95	2.802

The baseline unit, with a 6.51 m long heat exchanger requires 160.5 m^3 water annually (April-September), while if all parameters are applied the length of the cooler is reduced to 4.92 m and the water consumption decreases to 121 m^3. A 39 m^3 saving in water consumption and the cooling heat exchanger sizing is considerable for just one floor in a mid-rise building. But with all parameters applied, an extra 6 m^3 saving in water consumption, which means 1 m^3 of extra water-saving monthly, and the length is reduced by only 25 cm only, which is only a very small saving given the cost of the parameters and doubling the thickness of the insulation required to achieve it.

The average water evaporation in July/August is high because it is hot (55, 41.5 and 39.51 l/hr), where the highest saving was achieved when all parameters were applied because of the associated unit size reduction.

5.7 Chapter Summary

In this chapter, a simulation of dew point indirect evaporative cooler was prepared using the ϵ-NTU method for the heat exchangers, and a set of governing formulas were applied with the psychometrics of air properties. MATLAB simulation software was employed for this task; the code included a set of formulas that represents the performance of the cooler considering the geometric and operational parameters of the cooler (see Appendix C). The simulation output suggested the use of a heat exchanger with 44 channels (22 wet and dry pairs) referred to as a pack or a heat exchanger pack to be used for the overall cooler design depending on the cooling load of the building.

The MATLAB simulation of the dew point cooler used was further optimised, testing different lengths, channel gaps, channel air ratios and several air velocities, on the same heat exchanger pack size. The effects of varying each parameter were analysed. Twenty-four different simulations resulted from running the optimised parameters, where the parameters selected for the optimization were within the preferred ranges, which were informed by the previous simulation and experimental work by researchers in similar fields. For each of the selected simulation runs, a total of 4392 hours of weather for the house and flat units were used, where the simulation covered April to September on an hourly basis to allow selection of the best parameter in the 24 simulations. The best case was selected based on a preferred percentage of 75% cooling output and 25% water consumption as Kurdistan faces electricity supply issues to a much greater extent than problems with water supply. This is purely based on the experience and greater need for cooling than water, which helped to identify the best output simulation parameters for the pack among the simulations for design purposes.

Following the design of the heat exchanger pack and giving the priority of cooling output over water consumption, the output cooling of MATLAB for the total of 4392 hours has been coupled with the hourly cooling load for each of the case study buildings. The housing unit (case study 1) cooling requirement data was coupled with the designed cooling output of the dew point indirect evaporative cooler pack, in addition to the effect of each of the building parameters, to estimate the number of heat exchanger packs required to cover the hourly load of the building.

The peak sizing of the dew point cooling system does not follow the peak load; indeed, the peak sizing of the dew point is when the ambient air temperature is low, and the relative humidity is high, as this leaves the system unable to cover the required load in the building. The peak sizing of the dew point heat exchanger for the house unit was found to be in August, where the cooling load was less than the peak load for the hottest day in July due to the high humidity.

Some of the parameters applied were quite effective in reducing the sizing of dew point heat exchanger, as demonstrated in chapter 4, by applying efficiency measures to the building to reduce the cooling load which in turn affected the required sizing of the heat exchanger. The 3 cm insulation saved 0.73 m in the length of the exchanger, while increasing the insulation thickness from 3 to 6 cm did not have any significant effect on this length as this change only reduced the length by a further 13 cm (which is less than the size of a single heat exchanger pack), and where a 4 or 5 cm insulation thickness had an even smaller effect. A suspended ceiling was highly effective in reducing the length of heat exchanger. The orientation did not prove to have any significant effect on sizing or the length of the cooler's heat exchanger, showing only a 10 cm reduction at peak times for a given load. Double glazing or low emissivity glazing did not appear to have any particular effect on sizing reduction compared to the base model (which was 4.43 x 0.5 x 1.2 m long), but the hollow clay block allowed for a considerable reduction in sizing, totalling a 0.73 m reduction in length.

For the combined parameters, the maximum and optimum parameters were compared to the base model sizing of 4.43 m, where the use of a dew point heat exchanger system with the optimum parameters reduced the length to 3.17 m, saving 1.26 m. The maximum application of parameters would result in a length of 2.91 m. This further reduction of 0.26 m is relatively small compared to the original length and the number of parameters.

The water consumption rate/heat exchanger volume varied from one building to another because of the associated operating schedules. The rate of water evaporation or consumption for the house unit was calculated in all three cases based on a 100% load cover and using 100% fresh, outside air. For a cooling unit, the baseline size is a

4.43 m length cooling unit (2.65 m^3) heat exchanger, and an average annual of 30 l/hr of water is required which equates to 98.9 m^3 of water annually. The optimum sizing of a 3.17 m unit (1.904 m^3) uses only 72.93 m^3 water at annually 22.64 l/hr, saving almost 26 m^3, while a unit of 2.91 m for all parameters uses 67.238 m^3 annually, giving an annual rate of 20.73 l/hr.

The same procedure was applied to estimate the size of the cooler and the water consumption in the Heja city apartments (case study 2), taking each flat separately and the entire floor together. The results indicated that the peak sizing length for the dew point in the Flat A base model could be found as 2.45 m, while the effect of the optimum parameters would be to reduce this to 1.87 m, i.e., by 0.58 m, which represents a significant saving for just one flat. The maximum reduction that could be achieved by applying all parameters would be 1.79 m only, and thus not a large change from that of the optimum length. The annual water consumption for the base model was 61.9 m^3, while the optimum was 47.35 $m^{3,}$ and the maximum parameters were 45.34 m^3, which are very small for six months of operation.

For Flat B, the peak sizing was not coincident with the peak load day or time but was when the system could not cover the internal load and because of high humidity. The heat exchanger peak sizing was 1.53 m, while the optimum was 1.26 m, and with all parameters, this was reduced to 1.24 m, which is very small. The rate of water consumption for the baseline model was 33.3 m^3, 27.46 m^3 for the optimum and 26.89 m^3 for all parameters.

The peak load for Flat C did not indicate the peak sizing of the heat exchanger; rather, this was determined according to external weather conditions. The peak sizing to cover 100% of the load for the entire year was 1.84 m long for the baseline model. With optimum parameters, this length was reduced to 1.27 m, and the maximum parameters would reduce it to 1.2 m. The annual water consumption for the baseline was 20.62 m^3, 14.27 m^3 for the optimum, and 13.48 m^3 for all parameters.

Flat D is a small family apartment that contains one uncooled room. On the peak load day, the sizing of the heat exchanger was found to be just under one metre in length, which demonstrates that the peak load does not necessarily imply peak sizing of the dew point cooling system. The peak sizing for the heat exchanger was 1.67 m for the baseline, 1.23 m for the optimum, and 1.13 m for all parameters. The baseline unit uses only 18.12 m^3 of water annually, while the optimum unit consumes 13.4 m^3 and the all parameter unit 12.25 m^3. These are relatively small compared to the other flat units because of the reduced number of operating hours per week for this flat.

The entire floor of flats was also considered. The peak load was around 30 kW in July and August when the ambient temperatures were high, and where the peak sizing of the flat heat exchanger was found to be 3.35 m (because the unit is very effective at high ambient temperatures) and for the optimum was 2.43 m. The peak sizing for the entire floor of flats was when the unit was unable to cope with the internal and external load, and the ambient air was moderate and humid, which is a constraint to this unit, especially when it is using 100% fresh air as a single unit. The length of the baseline model was 6.52 m, the optimum was 4.92 m, and 4.86 m for the optimum parameters when the insulation thickness increased to 4 cm instead of the 3 cm thick, and the use of all parameters was 4.67 m long. The rate of water evaporation for the baseline model with a 6.5 m heat exchanger was a consumption of 160.45 m^3annually which represents an average of 45.02 l/hr/year, the optimum parameters will consume 121 m^3 of water, representing an average of 33.98 l/hr/year, and for all parameters a consumption of 115 m^3 water, which represents 39.51 l/hr/year. The reduction in size and water consumption is considerable when replacing the baseline with the optimum parameters (representing a 1.6 m reduction in length and a 39.3 m^3 saving in water).

CHAPTER 6: Economical and Environmental Analysis

6.1 Chapter Introduction

In this chapter, the merits of adjusting the fabrication of the base buildings using the optimum building parameters are assessed, with a feasibility study into the use of the dew point system carried out in comparison with the conventional split air conditioner commonly used in Kurdistan. The study involves an annual energy saving prediction, economic analysis and environmental assessment. The main aims of the chapter can be described as follows:

(1) The annual energy savings are predicted in the instances of adjusting the building fabrication and replacing the conventional split air conditioner with the dew point cooler, using the dedicated, dynamic simulation model.

(2) The economic acceptance is analysed, including the capital cost, annual operational costs and payback time for the conventional and dew point cooler applications, both with and without adjustments to the building fabrication.

(3) This environmental analysis is undertaken based on the annual CO_2 emission reduction for both cooler applications, both with the base models and after adjustments.

(4) Acceptance of the new dew point cooler with its merits and drawbacks.

6.2 Annual Energy Savings

The primary aim of the study is to reduce energy consumption, as obtained by adjusting the building fabrication of the base model buildings using the optimum building parameters determined in the case studies, as well as replacing the conventional split air conditioner with the dew point cooling system. Generally, the resultant energy savings could be between 14 and 26.8% for the buildings (house and the flats) through intervention in the building fabrication. However, when such adjustments are taken together with replacing the air conditioner, the energy savings could be vast, in the region of 89 to 91% depending on the building position and operating schedules. If the annual energy savings for each of the case studies are assumed 90%, the first project, the Ashti study, which consists of 4000 housing units, could save up to 47.7 MWh annually.

Similarly, the Heja apartments project the second case study, which consists of 11 blocks where each block itself consists of four storeys of four flats. It could be seen the annual energy savings reaching as high as 1.124 MWh. Table 6-1 shows the percentage energy savings for each of the case study models in the instance of applying the optimum parameters as a set of interventions, and when using these same optimum building parameters in combination with replacing the air conditioner.

Table 6-1: Effects of the use of dew point system and optimum parameters on percentage annual energy savings

	Optimum parameter %	**Dew point + Optimum %**
House model	26.17	90.77
Flat A	16	89.43
Flat B	14.1	89.2
Flat C	26.79	90.84
Flat D	25.83	90.72
Combined Flats	18.64	89.83

The lion portion of the investments on the residential projects is in Erbil, including 71 housing projects (44164 different housing units) and 24 apartment projects (18631 different flat units). With the assumption of the house of the case study 1 and an average flat of case study 2 as samples for all over Erbil projects, and the annual energy saving for each of them is 90% with adjusting the building fabrications and replacing the coolers. The total annual energy saving for Erbil's projects could be estimated as 23,462MWh that help to solve the power cut energy in Erbil. Table 6-2 illustrates the details of the annual saving for Erbil's overall projects.

Table 6-2: Estimated annual energy saving with building adjustment and replacing cooling systems in total housing projects in Erbil.

Erbil projects, 71 Housing + 24 Flat	Original estimated consumption, kWh	Saving Optimum with base, kWh	Saving with dew point only, kWh	Saving Optimum + Dew, kWh	Final possible annual saving , kWh
No of Houses, 44164	231,507,688	60,593,008	202,571,435	210,132,312	**21,375,376**
No of Flats, 18631	51,011,678	27,629,773	44,621,245	48,925,006	**2,086,672**
Total energy consumption	**282,519,366**	**88,222,781**	**247,192,680**	**259,057,318**	**23,462,048**

6.3 Economic Analysis

In a hot and dry climate, organizing and reducing energy consumption is vital due to the high energy consumption of air conditioning systems. The economic side is a key parameter in any project, including HVAC. Hence, an economic analysis must be considered in the first planning stage to avoid project failure, where the analysis considers both the capital cost and operational costs to assess the payback time (PBT), the accuracy of which are vital to protecting the project from failure. USA dollars (US$) has been used for the economic analysis of this study.

6.3.1 Estimated Capital Costs

6.3.1.1 Split Air Conditioner

The split air conditioner is the most commonly used in Iraq; its cost is not stable and varies due to trade and market issues, quality, availability of spare parts, and brand. After making online, market, and over the phone enquiries with wholesalers, the price of the split air conditioner could be estimated. An average, medium quality air cooling system is about \$300-450/ton of refrigeration (1 ton = 3.51 kW), so the cost will be around \$107/ kW of cooling for the external unit [170], whilst the indoor unit is estimated to cost around \$140-160 per unit [171] [172]. The cooling capacity was taken into account when estimating these figures. The installation, and sizing of the air conditioners are not performed by professionals, but rather purely depends on the wholesalers' advice, who is not a professional, or sometimes the technicians who install the coolers. Most people install one unit per zone, which result in a huge, and often unnecessary, rise in energy consumption. In this study, the air conditioner for the house model is assumed to constitute two outdoor units feeding six internal units, as the split is comprised of two parts. A 10 kW and a 7.5 kW were used in the calculations. The same procedure was followed for the flats, using one outdoor and five indoor units each for Flats A, B and C and four internal units for Flat D for the capital cost calculations. For the entire floor of flats (four flats), two outdoor and 19 indoors units were assumed.

For the house base model, with a peak cooling load of 17.5 kW, the simulation results were used to calculate the electricity consumption with a COP of 2.5 [88] [89]. The capital cost of the split air-conditioner for the base model and the model with optimum building parameters assumed were calculated and are illustrated in Table 6-3 based on the cooling load of the building, and consequently the load of the cooler. For the base house model, the total capital cost was \$2772, which dropped to \$2183.75 after adjusting the building fabrication. For the flat base models, the capital cost ranges from \$1500 to \$1820, and which decreased to \$1391 to \$1602 after applying the optimized parameters to the building.

Table 6-3: The estimated capital cost using split coolers (house and flats)

Building	Base model,$	Optimum, $
House	2772	2184
Flat A	1820	1605
Flat B	1500	1391
Flat C	1820	1500
Flat D	1713	1391
Total flat	6274	5310

6.3.1.2 Indirect Evaporative Dew Point System

The indirect evaporative dew point cooler is a new type of cooling system; its cost is consequently much higher than that of typical air conditioning systems as the technology is still in development [173]; this said, the price is continuously declining over time due to increased large-scale production. However, despite being well known in China and India, it still hard to obtain such units in different sizes. So, in this study, the capital cost was estimated to be $225/kW based on online market research and over phone contact with the manufacturers [174], where the price above includes the delivery cost. The capital cost of the dew point cooler for the house base model was $3937, which decreased to $2700 after adjustment of the building. All capital costs associated with the dew point air conditioner for the base model and the model using optimum parameters are illustrated in Table 6-4.

Table 6-4: The estimated capital costs using the dew point cooler (house and flats)

Building	Base model, $	Optimum model, $
House	3937	2700
Flat A	2250	1800
Flat B	1575	1462
Flat C	2250	1575
Flat D	2025	1463
Total flat (central) [174]	7200	5625

6.3.2 Annual Operation Cost

6.3.2.1 Split Air Conditioner

Operation cost is the cost that has to be paid to operate a set of equipment. In air conditioning, annual operating costs depend on the type of system being operated, and the type of fuel being consumed. The calculation of operational costs for the conventional split air conditioner consists of the energy costs, which is the electricity used to operate the cooler plus maintenance costs; the latter is between 1.5-2% of the capital cost and is assumed for our purposes to be 1.5% [175]. Electricity prices in Kurdistan are slightly different from those in central Iraq. The average cost of a kilowatt-hour is $0.059 [176]. Table 6-5 and Table 6-6 are illustrating the annual operational costs of the house and the flat units, including the costs for both the base and the adjusted models. As there is a significant saving in energy consumption, this is reflected in the operational costs saving as well. The base model requires a higher cooling load, which means higher capital costs and consequently greater maintenance and operational costs. This results in a $90 annual operational cost saving for the house unit only, whilst with the adjusted model with the optimum building fabrications the saving could be up to $32 for a single flat depending on the scheduling of the flat’s operational hours, and for the entire storey of four flats, is $113.

Table 6-5: Annual operational costs using the split air-conditioner (house)

	Base model	Optimum
Cooling capacity, kW	17.5	12
Electricity cost, $/kWh	0.06	0.06
Calculated electricity, kWh	5241.6	3870.0
Consumed Electricity, kWh, $	314.5	232.2
Maintenance cost, $	33.27	26.21
Annual operational cost, $	**347.7**	**258.4**

Table 6-6: Annual operational costs using the split air-conditioner (flats)

	Flat A Base	**Flat A Optimum**	**Flat B Base**	**Flat B Optimum**
Requirement, kW	10	8	7	6
Electricity cost $/kWh	0.06	0.06	0.06	0.06
Calculated electricity, kWh	3448.2	2913.6	2470.0	2121.8
Consumed Electricity/kWh, $	206.89	174.8	148.2	127.3
Maintenance cost, $	27.3	24.09	22.49	20.88
Annual Operation cost, $	**234.2**	**198.9**	**170.7**	**148.2**
	Flat C Base	**Flat C optimum**	**Flat D base**	**Flat D optimum**
Requirement, kW	10	7	9	6
Electricity cost, $/kWh	0.06	0.06	0.06	0.06
Calculated electricity, kWh	1675.2	1226.4	1220.1	904.8
Consumed Electricity /kWh, $	100.5	73.6	73.2	54.3
Maintenance cost, $	27.3	22.5	25.7	20.8
Annual Operation cost, $	**127.8**	**96.8**	**98.9**	**75.2**
	Total flat	**Optimum total flat**		
Requirement, kW	32	25		
Electricity cost, $/kWh	0.06	0.06		
Calculated electricity, kWh	8813.5	7166.7		
Consumed Electricity/kWh, $	528.8	430.0		
Maintenance cost, $	94.1	79.6		
Annual Operation cost, $	**622.9**	**509.6**		

6.3.2.2 Indirect Evaporative Dew Point System

The operational costs of dew point evaporative cooling systems include the cost of water in addition to that the electricity and maintenance costs because the system needs water for operation. There is a nominal price for water in Kurdistan which is as low as \$0.325/m^3, \$0.059/kWh for electricity and 1.5% of the capital cost for maintenance. Table 6-7 and Table 6-8 illustrate the annual operational costs of the house and the flat units, including both costs for the base and the adjusted models. As clarified for the split air conditioner operational cost, the base model has a higher capital cost and consequently greater maintenance and operational costs. This gives a \$37 annual operational cost saving for the house unit only with the adjusted model, whilst the saving could be up to \$16 for a single flat depending on the scheduling of the flat's operational hours, and for the entire storey of four flats is \$49.

Table 6-7: Annual operational cost using dew point system (house)

	Base model	Optimum
Cooling capacity, kW	17.5	12
Electricity cost, \$/kWh	0.06	0.06
Calculated electricity, kWh	655.2	483.75
Consumed Electricity/kWh, \$	39.3	29.02
Water cost @ 0.325 m^3	32.17	23.72
Maintenance cost, \$	59.05	40.5
Annual operational cost, \$	**130.5**	**93.24**

Table 6-8: Annual operational cost using the dew point system (flats)

	Flat A Base	**Flat A Optimum**	**Flat B Base**	**Flat B Optimum**
Electricity, kWh	431.03	364.2	308.7	265.23
Water amount, m^3	61.90	47.30	33.32	27.46
Water cost, $	20.12	15.37	10.83	8.92
Electricity cost, $	25.86	21.85	18.53	15.91
Annual maintenance cost, $	33.75	27.00	23.63	21.94
Annual Operation cost, $	79.73	64.23	52.98	46.78
	Flat C Base	**Flat C optimum**	**Flat D Base**	**Flat D optimum**
Electricity energy, kWh	209.4	153.3	152.5	113.11
Water amount, m^3	20.62	14.27	18.12	13.40
Water cost, $	6.70	4.64	5.89	4.36
Electricity cost, $	12.56	9.20	9.15	6.79
Annual maintenance cost, $	33.75	23.63	30.38	21.93
Annual Operation cost, $	53.02	37.46	45.41	33.07
	Total floor	**Total floor optimum**		
Electricity, kW	1101.69	895.84		
Water amount, m^3	160.50	121.00		
Water cost, $	52.16	39.33		
Electricity cost, $	66.10	53.75		
Annual maintenance cost, $	108.00	84.38		
Annual Operation cost, $	**226.26**	**177.45**		

6.3.3 Payback Time (PBT)

Payback time (PBT) is the time required to regain the total capital cost of a system, excluding discounts. If the payback time is less than the life span of a system, then the energy saving can contribute to an overall reduction of CO_2 emissions [66] [177]. The lifespan of air conditioning equipment is in the region of 15-20 years in Iraq, but due to the harsh climate is taken as 15 years for our purposes [88]. The payback period for operating a dew point cooling system as a replacement to a conventional split air conditioner can be estimated as:

$$\textit{PBT (years)} = \frac{\boldsymbol{Capital\ cost}_{\boldsymbol{dew}} - \boldsymbol{Capital\ cost}_{\boldsymbol{split}}}{(\boldsymbol{Split}_{\boldsymbol{electricity}\,\$} - \boldsymbol{Dew}_{\boldsymbol{electricity+water}\,\$}) + (\boldsymbol{Split}_{\boldsymbol{maintenance}\,\$} - \boldsymbol{Dew}_{\boldsymbol{maintenance}\,\$})}$$

If the conventional air conditioning system is replaced with the dew point system for the base house model, the PBT is 4.57 years, and for the flats is between 0.72 to 4.82 years due to the differences in their operational times and cooling loads. With the adjusted model and replacing the cooling system taken together, the PBT of the house model decreased to 2.68 years, while for the flats declined to 0.72 to 1.56 years, with a different PBT reduction rate. Table 6-1 Table 6-9 shows the PBT of the house and flats in the instance of replacing the conventional cooler in the base models with the dew point system, as well as the when taking the adjusted model and replacing the cooler together. The capital cost of installing building fabrication is not included in the calculations.

Table 6-9: Payback period for using both the dew point cooling system and building intervention improvements together

Payback Time (years)		
	Base model + Dew point	**Optimum + Dew point**
House model	4.57	2.68
Flat A	3.02	1.56
Flat B	0.72	0.68
Flat C	4.82	1.11
Flat D	4.53	1.32
Combined Flat	2.40	0.97

6.4 Environmental Effects

Carbon dioxide (CO_2) is the main greenhouse gas emitted by human actions, so to analyse the environmental effect of energy systems, CO_2 is usually considered. Although there is a combination of harmful gases that can also be emitted, the largest portion by far is CO_2. Generally speaking, the Middle Eastern countries are reliant on fossil fuels to generate electricity. According to scientists, the global CO_2 concentration is 40% higher than the mid-1800s. Iraq is one of those countries that rely heavily on fossil fuels to produce its energy and mainly relies on oil to produce electricity. The associated demand is increasing with time and population, such that CO_2 emissions have increased by 169% between 1990 and 2014 [178]. Iraq's CO_2 emissions factor is 0.907 kgCO_2/kWh for every kWh of electricity consumed [179], which is a very high figure compared to European and other developed countries, this is because Iraq suffered from many wars during the last few decades that affected on the development of the country. Using old equipment as well as the high rate of insufficient fossil fuel generators (e.g. diesel generators and heavy oil) are the main reason for the high figure of the carbon factor. Sources of clean energy are not generally available in Iraq, apart from a few hydropower dams that produce an essentially insignificant amount of electricity due to lack of maintenance. Table *6-10* shows the annual CO_2 emission for both case studies and both coolers, including the base models and the adjusted models with optimum parameters. The results show that the CO_2 emission declines when using the optimum parameters due to the reduction in energy consumption; there is a further reduction when replacing the coolers for the dew point systems in addition to using the optimized parameters.

Table 6-10: Annual CO_2 emissions for the house and flats for both the split air conditioner and evaporative cooler

	Annual CO_2 tonnes/kWh production			
	Conventional air conditioning.		Dew point system	
	Base model	**Optimum**	**Base model**	**Optimum**
House	4.75	3.51	0.59	0.44
Flat A	3.13	2.64	0.39	0.33
Flat B	2.24	1.92	0.28	0.24
Flat C	1.52	1.11	0.19	0.13
Flat D	1.10	0.82	0.14	0.10
combined floor flats	8.00	6.50	1.0	0.81

Following the calculation of the annual CO_2 emissions, the annual CO_2 emission reduction can be calculated in the instance of applying the interventions to the building using optimum parameters, as well as the building improvements in addition to replacing the conventional split with the dew point cooler. The results of these calculations are illustrated in Table *6-11*, which shows the annual CO_2 emissions for the adjusted house model is 1.2 tonnes and reaches 4.3 tonnes when using the adjusted model in combination with replacing the coolers. Purely applying a set of interventions to the building fabrication of the flats could reduce emissions by 0.3 to 0.5 tonnes/year. However, with the building fabrication improvement in combination with replacing the cooler, the associated reduction increased to 1-2.8 tonnes/year.

Table 6-11: Annual reduction in CO_2 emissions in the house and flats

Annual Co_2 reduction (ton)		
	Optimum	Dew point cooler + Optimum
house	1.2	4.3
Flat A	0.5	2.8
Flat B	0.3	2.0
Flat C	0.4	1.4
Flat D	0.3	1.0
Combined floor	1.5	7.2

If the same process of the annual energy saving for overall Erbil's projects in Table 6-2 is followed. The annual CO_2 reduction could be assumed that reaches 223,696 ton for Erbil's projects; more details are illustrated in Table 6-12.

Table 6-12: Possible annual CO2 Production and saving/ton

Erbil projects, 71 Housing + 24 Flat	**Original CO2 ton**	**CO2 with Optimum**	**CO2 with Dew point**	**CO2 Opt + dew point**	**Annual CO2 possible reduction, Ton**
No of Houses, 44164	209,779	155,015	26,056	19,432	**190,347**
No of Flats, 18631	37,075	30,182	4,657	3,726	**33,349**
Total CO2	246,854	185,197	30,714	23,158	**223,696**

6.5 Regional Acceptance of Newly Developed Cooler

6.5.1 Cooler Location in the Buildings

The position of the cooler is not a particularly significant issue in Kurdistan because, in general, the houses are sufficiently large to locate the cooler in any suitable place depending on the zones and their cooling requirements. The single split air conditioner normally consists of two parts and are wall-mounted; however, the multi-split system has the indoor parts mounted on the walls and where the main outdoor unit could be located outside of any room on the ground as there is enough space for such. The buildings are always flat-roofed, and most are detached, as mentioned earlier in this study. Therefore, for the house unit it is possible for any cooling system, regardless of the size, to be installed without issue, even if ducts are used for the air distribution. It is also possible for such units to be placed in the pathways on the ground floor as they are generally not used for other purposes, or they can otherwise install them on the rooftop.

For multi-storey buildings such as the Heja apartments, the cooler could be installed on a side pathway, on the ground floor or on the rooftop and then connected to ducts for distribution to the appropriate zones. While the large size of the dew point system is a particular problem with the technology, for Kurdistan, this is not considered to be problematic. Dew point systems needs water for their operation, though again this is not a significant problem as they consume much less water than the direct evaporative coolers that are still used in Kurdistan. Water can be supplied easily and directly from the mains, or from the rooftop water tank that is available on every house in Kurdistan. Figure 6-1 shows the suggested locations of the coolers for both case study buildings.

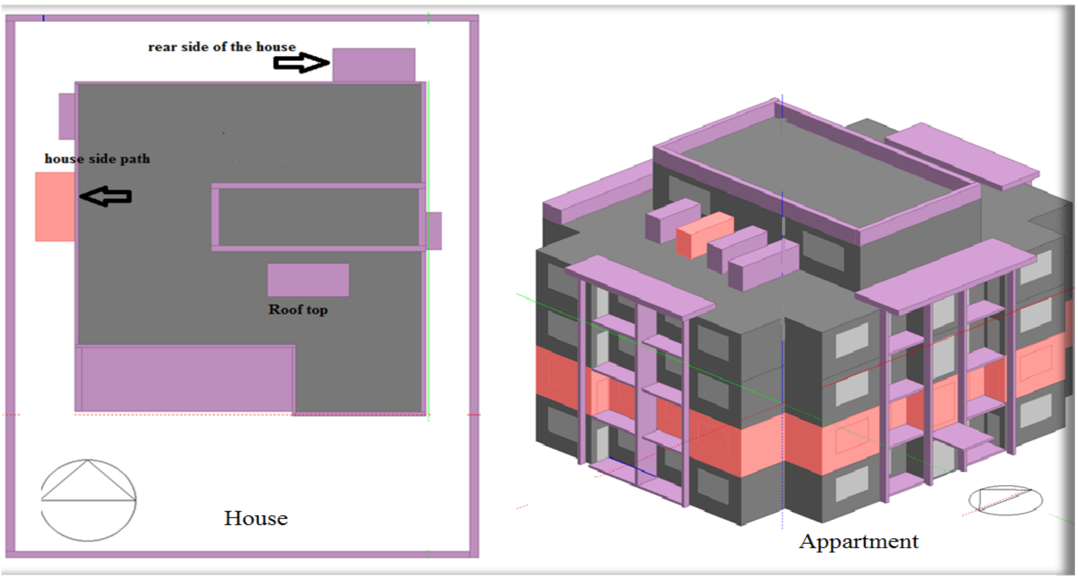


Figure 6-1: Dew point cooler location for the house and apartment

6.5.2 Air Quality and Health Issues

In Kurdistan, the split air conditioner that provides cold air to single zones circulates air at the minimum ventilation rate or, in many cases, with no ventilation depending on the opening of doors or windows. In summer, when the cooling is in operation, windows are tightly closed to prevent the cold air escaping. This increases the indoor CO_2 concentration and leads to poor indoor air quality because of human breath and unwanted odours from the building and furniture [45]. According to the study of these different systems, the split air conditioner results in the highest levels of CO_2 [180]. On the other hand, indirect evaporative air conditioners (IDEC) provide 100% fresh air from outside at a very high rate of ventilation in the building, resulting in good indoor air quality [177].

The issues that prevent the more widespread use of the direct evaporative cooler is the resultant increase in humidity inside the building because of the water that must be directly sprayed into the cooling zone. This problem is solved in the indirect evaporative dew point cooler in that it admits cool, low humidity air into the cooling zone. The dew point cooler could, as a further advantage, prevent legionnaires' disease, whose bacterium can develop and spreads through direct contact with cooling water droplets. Hence, the indirect evaporative dew point cooler can overcome this problem as there is no direct contact with the water droplets.

In conclusion, the dew point cooler is healthier than the split air conditioner due to the constant supply of fresh air to the cooling zones. In addition, it is better than direct evaporative coolers because the humidity is low, and hinders the development of the *Legionella* bacterium [181]; furthermore, the dry and hot climates typically of Iraqi summertime require the bit of humidity which comes directly from outside, with the conditioned air with Erbil’s humidity [165] being between dry and moderate.

6.6 Chapter Summary

This chapter presents the results of the study, including the potential economic and environmental advantages of adopting its findings. The main objective of the study, which is to determine energy savings, has been verified. The energy savings in residential buildings are estimated to be 14 to 26.8% purely by adjusting building fabrication. However, by adjusting the fabrication and simultaneously replacing the air conditioner, these savings could be considerable, ranging from 89 to 91%, with the associated savings vary depending on the building position and the associated operating schedules. If the annual energy savings for both case study's projects are assumed to be 90%, the first project, the Ashti study, which consists of 4000 house units, could save up to 47.7 MWh annually; similarly, the Heja apartments project, that consists of 11 blocks where each block has four stories, and each storey comprises four flats, the annual energy savings could reach as high as 1.124 MWh.

An average and medium quality air cooling system costs about $300-450/tonne of refrigeration cooling, and so it will be $107/kW for the external unit, while the indoor unit is estimated to be around $140-160 per unit. Most people install one unit per zone, which increases the associated energy consumption considerably. The air conditioner for the house model is assumed to constitute two outdoor units feeding six internal units, as the split comprises of two parts. 10 kW and a 7.5 kW were used for the above, respectively, in subsequent calculations. The same procedure was followed for the flats, using one outdoor and five indoor units for Flat A, B and C, and four internal units for Flat D for the capital cost calculation. For the entire floor of flats (four flats) two outdoor and 19 indoor units are assumed.

For the house base model, a total cooling load of 17.5 kW was found. The capital cost of the split air-conditioner for the base model and the adjusted building with the optimum building parameters were calculated. For the base house model, the total capital cost was found to be $2772, which subsequently dropped to $2183.75 after applying the adjustments to the building. For the flat base models, the capital cost ranged from $1500 to $1820, decreasing to $1391 to $1602 when applying the improvement interventions to the building.

The annual operational costs were calculated, which comprised the maintenance and electricity costs, as well as the cost of the water required for the dew point cooler as it also needs water for its operation. The maintenance costs were assumed to be 1.5% of the capital costs. The cost of electricity in Kurdistan is \$0.059/kWh, while the cost of water can be as low as \$0.325/m^3.

The energy savings and capital cost reduction result in a \$90 annual operational cost saving for the house unit only when adjusting the house model to use the optimum building fabrication, whilst the savings could be as much as \$32 for a single flat depending on the scheduling of the flat's operational hours and \$113 for the entire storey of four flats.

If the conventional air conditioning system is replaced with the dew point system for the base house model without building adjustment, the PBT was found to be 4.57 years, whilst for the flats, the PBT varied between 0.72 and 4.82 years due to the difference in operational times and cooling loads. With the application of the set of interventions to the models and the simultaneous replacement of the cooling systems, the PBT for the house model decreased to 2.68 years while the PBT for the flats declined to 0.72 to 1.56 years, with the same provisos as above.

The annual CO_2 reduction for the adjusted house model was 1.2 tonnes, reaching 4.3 tonnes when applying the building parameter interventions and simultaneously replacing the coolers. Improving the building fabrication of the flats alone could reduce emissions by 0.3 to 0.5 tonnes/year, whilst applying the set of interventions and simultaneously replacing the cooler, the CO_2 reduction could be 1 to 2.8 tonnes/year.

The dew point air conditioner has the disadvantage of being very large; however, this is not considered to be an issue in Kurdistan because the buildings, especially houses, tend themselves to be rather large. Additionally, they have other merits that might lead to their acceptance by the people, such as their high efficiency in hot and dry climates (thus reduced energy consumption), low water consumption in comparison with direct evaporative coolers, and the use of fresh supply air in comparison with the split air conditioner. Besides, they can help to prevent infection by the Legionella bacterium because there are no water droplets in the supply air.

CHAPTER 7: Discussion, Conclusion and Further Work

7.1 Discussion

This research has studied the potential for energy savings in residential buildings in Kurdistan. It has investigated building fabrication parameters and their influence on reducing the cooling load on air conditioning systems. The performance of the dew point cooler was examined using computer modelling and optimization, whilst an economic, environmental and acceptance analysis of the cooler in Kurdistan was also undertaken. The key results are summarised in the following statements:

Context and case studies: A very large portion of the domestic energy consumption is used in air conditioning during the summertime. The Kurdish government in Northern Iraq has simplified and supported investment projects to cover the housing shortages in the region. The case studies are just two examples of the typical and widespread type of buildings among the housing projects.

A one-storey building was chosen as the first case study because it is the most desirable, affordable and privately owned house type (villa). It is a housing unit from Ashti project, which consists of 4000 similar units across Erbil city in the residential project. The second case study is the low-rise apartment building from Heja City project that consists of eleven units with four floors; each floor comprises of four apartments on each floor. These two chosen building models are the most typical among the housing projects towards the aim of minimizing energy consumption in cooling. The geometrical dimensions and building fabrication were taken from the published data and direct contacts with the executive companies as secondary data. The chosen case studies became a basis of the modelling and prediction of the cooling load of the air conditioning for each building.

Cooling load of the selected buildings: Applying a set of intervention parameters to the buildings had a very clear impact on the cooling load and annual energy savings. The primary results of the simulations showed that the house and the flat base models' cooling systems consume 78% and 79% of their total domestic energy consumptions, respectively, in maintaining the internal zone temperatures at the comfort level of 25°C. The energy consumption by other equipment in the house and the entire floor of flats was 15% and 7%, respectively, while the lighting consumed 7% and 14%, respectively.

There are many effective parameters on the cooling load that result in minimizing the load, consequently reducing the energy consumption. The applied parameters of, hollow clay block, 6 cm insulation and added suspended ceiling, low emissivity glazing and the overhang on external windows, along with the original South-facing orientation of the house gave the best energy savings and load reduction. It showed that the peak load could be reduced from the 17.47 kW of the base model to 9.92 kW after adjustments, while the annual consumption reduced to 9390kWh. However, if the parameters of 3 cm thick insulation, clay blocks, with the suspended ceiling were applied, the cooling load was reduced to 11.16 kW and the energy consumption to 10,141 kWh. The difference between the two is relatively small when compared to the number and complexity of the changes, such as overhangs, doubling the thickness of the insulation and the use of low emissivity double-glazing. Analysis of the complexity and costs of installing all the construction material measures to allow for maximum savings led to the conclusion that a set of parameters that addressed the compromise between ultimate performance and cost of installation was given using 3 cm thick external insulation, a suspended ceiling and a hollow clay brick construction. The double glazing or low emissivity window, as well as adding overhangs over the windows, have a very limited effect on load reduction or energy savings. The suspended ceiling alone was considered to be adequate in terms of insulation, energy savings, and cooling load reduction.

For the apartment model, the annual energy consumption and cooling load for each flat vary depending on the number of occupants and the operation schedules, as well as the orientation and location of the flat within the building. The results showed that the clear double-glazing with the suspended ceiling has no effect on the cooling load and energy savings. External window overhangs and low-emissivity glazing have a small influence, but the latter has slightly greater effect. The maximum parameters, namely 6 cm insulation, clay blocks, low emissivity double-glazing, overhangs and suspended ceiling, have been applied to all flats separately and all combined flats. For the first floor flats, the annual energy saving was ranged from 12.18% to 31.8% and 22.26% for the combined flats.

The same parameters with the 3 cm thick insulation showed a 21.39% annual saving, which is a less than 1% difference in savings. For this floor, it was observed that adding the suspended ceiling actually had a negative impact on cooling load and energy savings, so there is no need for this addition in any of the flats, except of the top floor flats that behave more like a single house as it is directly exposed to the external environment and solar irradiation. Using 3 cm instead of 6 cm of insulation and keeping all other parameters unchanged for all flats and the combined floor did not make any significant difference to cooling load or annual energy savings, so the 3 cm insulation is considered the optimum thickness in terms of cost versus efficiency. The optimum parameters for the house were found to be the hollow clay blocks, 3 cm thick insulation and a suspended ceiling, while in the flats the optimum parameters were clay blocks, 3 cm thick insulation and low emissivity double glazing. The results showed that for the existing building 3cm extra insulation on the external wall would cover the effect of the clay block, the clay blocks effect is equivalent to an extra 2cm insulation with low emissivity glazing for the house, and 2cm insulation with overhangs for the flats, if the buildings retrofitted.

The daily peaks in the cooling loads between July and August were selected for the house base model. The daily peak loads were averaged for cooling load reduction purpose, and the unmet hours are those that exceed the set temperature of 25^{o}C; the method resulted in 28.8% cooling load reduction for house model. For the individual flats, the same method reduced the cooling load by 19% to 37%, while the unmet hours rose up the indoor temperature up to 30^{o}C for the house and flats.

For the combined flats, the same procedure was followed and was similarly assessed. The cooling load reduced by 29%, but the unmet hours will be as high as 200 hours with temperature over 29^{o}C. That is why another averaging method was used for the combined flats only, where the peak weeks' average cooling load was used, and this method raised the average load line to 26.77 kW, though the use of this method left only 31 unmet hours.

It is vital that if the cooling were supplied to a building with a fixed schedule, then the daily method would be extremely beneficial in terms of predicting the best coverage for cooling hours and possible reductions in the capacity of the cooling systems. In case of if the approach of the daily peak did not work well because of the high number of unmet hours, and when multiple zones combined to provide cooling, then the weekly average peak method should be used instead.

Dew point cooling system, design, optimization and application: A simulation representing an indirect evaporative dew point cooler, as based on previous research, was prepared using the є-NTU method for the heat exchangers. Several governing equations were used with the psychometric of air properties, such as dry bulb temperature and relative humidity of ambient air. The MATLAB simulation software was employed to achieve the task. The simulation output was based on a heat exchanger of 44 channels (22 wet and dry pairs) referred to as a ‘pack’ for use in the overall cooler design, as depending on the cooling load of the building.

Following the optimization, the best-case parameters for the design of the dew point cooler were selected as based on a preferred sums percentage of 75% cooling output and 25% for the water consumption, as Kurdistan faces more problems with electricity supply than for water. The simulation was selected based on the sum of the cooling output and water consumption during the hot season.

The output of the dew point cooling capacity and water consumption from the MATLAB simulation was coupled with the hourly cooling requirements for the case study buildings (house and flats). The house unit (case study 1) cooling requirement data was coupled with the cooling by the dew point indirect evaporative cooler to estimate the number of heat exchanger packs required to cover the hourly load of the buildings, and also to estimate the effects of each building fabric parameter that was used on the dew point packing size.

The required size of the dew point cooler was determined by calculating the required maximum size for each hour. The maximum required size does not inevitably coincide with the peak cooling load; in fact, the peak size of the dew point was when the ambient air temperature is low, and the relative humidity is high, thus rendering the system unable to cover the required load in the building. The simulation aimed to minimize the size of the dew point heat exchanger as much as possible. The largest or the peak size of the dew point heat exchanger for the house unit was found to be in August, when the cooling load was less than the peak load during the hottest day in July because of the slightly a higher humidity in August, as taken from real weather data.

When the effect of the parameters on the heat exchanger sizing was analysed in the buildings, some of the applied parameters found to be effective in reducing the size of dew point heat exchanger. The base model house heat exchanger size was found to be 4.43 x 0.5 x 1.2 m long. Individual parameters had separate effects on the length of the cooler. The 3 cm thick insulation saved a 0.73 m additional length while increasing that insulation from 3 to 6 cm did not have any significant effect. A suspended ceiling in the house had a significant effect in terms of reducing the length of heat exchanger. The orientation did not have any significant effect on sizing or length of the cooler’s heat exchanger. Double glazing or low emissivity glazing did not have a significant effect on heat exchanger pack length reduction compared to the base model, but the hollow clay block allowed for a large reduction in sizing, namely a 0.73 m reduction in length. With the optimum parameters applied to the house allowed a reduction in length to 3.17 m, saving 1.26 m. Moreover, with maximal parameters, the heat exchanger length will be reduced to 2.91 m.

Water consumption rate per heat exchanger volume varied from one building to another due to the associated operating schedules. For a cooling unit baseline model with a 4.43m length and 2.65 m^3 volume heat exchanger, the annual water consumption is 98.9 m^3. The optimum length of 3.17 m of HXC volume of 1.904 m^3 used only 72.93 m^3 of water, saving almost 26 m^3 water, while a 2.91 m long unit with all maximized parameters, the annual water evaporation found to use 67.238 m^3.

For the flat model, the second case study to estimate the size of the dew point cooler and related water consumption, taking each one of the studied flats independently and the whole floor flats as one combined unit to size the dew point indirect evaporative cooler. It was found that the peak size length for the dew point cooler in the Flat A base model was 2.45 m in length, whilst the effect of optimum parameters was to reduce this to 1.87 m, which represented a significant reduction in length for one flat. The maximum reduction from applying all parameters resulted in a length of 1.79 m only, which did not represent such a large change from the optimum length (only 8 cm reduction). The annual water consumption for the base model was 61.9 m^3, while for the optimum was 47.35 $m^{3,}$ and for the all parameters were 45.34 m^3, the latter is representing only a very small difference for six months operational time. In Flat B, the peak size of the cooler was not on the peak hot load day and time, but the peak heat exchanger sizing was found to be when the system could not cover the cooling load of the flat due to the outside air temperature and high humidity, which required a larger size to cover the load. The heat exchanger peak size showed 1.53 m in length, while the optimum was 1.26 m and with all parameters the length reduced to only 1.24 m, which again was only a very small reduction from the optimum (only 2 cm). The rate of water consumption for the baseline model for Flat B was 33.3 m^3, for the optimum is 27.46 m^3, and for all parameters is 26.89 m^3.

In Flat C, the peak size to cover 100% of the building load over the year was 1.84 m for the baseline model. With optimum parameters, this figure reduced to 1.27 m (57 cm reduction from baseline) and the length with all applied parameters was only 1.2 m long. The annual water consumption for the baseline heat exchanger unit was 20.62 m^3, 14.27 m^3 for the optimum parameters and 13.48 m^3 for all parameters.

The peak sizing for the heat exchanger for the baseline model of Flat D was found to be 1.67 m, the optimum sizing was calculated as 1.23 m, and the length for all parameters was 1.13 m. The baseline unit annual water consumption was only 18.12 m^3 of water, while the optimum was 13.4 m^3 and for all parameters was only 12.25 m^3. This was a relatively small value compared to the other flat units because of the reduced number of operating hours per week required in this flat.

A 30 kW load for the baseline combined floor flats model in July and August when the ambient temperatures were high; in the peak day, the length for the flats' heat exchanger found to be 3.35 m because the unit is very effective at high ambient temperatures and low humidity. The length of the heat exchanger was reduced to 2.43 m using the optimum parameters for the same temperature and humidity. The peak length of the dew point heat exchanger in the year for the baseline model was 6.52 m, 4.92 m (3 cm insulation) for the optimum, and 4.86 m (4 cm insulation) for the maximum optimum parameters and the length of the cooler in case of all parameters applied reduced to only 4.67 m. The annual water consumption of the combined flats with 6.5 m long heat exchanger is 160.45 m^3, whilst with the optimum parameters consumes 121 m^3, and with all parameters will consume 115 m^3. The reduction of size and water consumption was considerable when replacing the baseline with the optimum parameters, (1.6 m length reduction, and an annual saving of 39.3 m^3 of water).

Generally, the sizing of the heat exchanger is proportional to the buildings cooling load for any particular climate. Designing of the heat exchanger size is not necessary to be on the peak design (hottest) day, as it is affected by the external weather conditions and mainly humidity, as it is not effective at high humidity rates. Therefore, for the hot/humid climates applications, it is vital to be accompanied with the dehumidifier such as a desiccant wheel, for higher efficiency.

Economic and environmental analyses: The energy-saving was the main objective of the research and it was obtained by applying a set of interventions to the buildings and replacing traditional coolers with the indirect evaporative dew point coolers. The energy-saving could reach 26.8% by adjusting the building fabrication, and 91% when concurrently improving the building fabrication and replacing the air conditioner. With a 90% annual energy saving assumption, the Ashti project that consists of 4000 similar designs of housing units could save up to 47.7MWh annually. For the Heja apartment project, which consists of 11 blocks, each block with four stories and each story including four flats, the annual energy saving estimation could reach 1.124 MWh. As the majority of residential building projects are in Erbil, namely a 71-house project that consists of 44,164 houses and 24 apartment projects consisting of 18,631 flats, the predicted energy savings for all these residential units could reach 23,462.048 MWh, consequently solving the power issues in the city.

The annual operational cost savings for the house unit, if adjusted with the ideal parameters for the building fabrication, could reach \$90. This amount of savings is less in the Flat building, which could be up to \$32 for a single flat reliant on the scheduling and operating hours, and where the savings for the entire floor will reach about \$113. If the conventional air conditioning system is replaced with the dew point indirect evaporative cooling system for the base house model without adjustment, the Payback Time (PBT) was 4.57 years, and for the flats ranged between 0.72 to 4.82 years due to the differences in operation times and cooling loads. With the improved fabrication and simultaneously replacing the cooling systems, the PBT of the house model was reduced to 2.68 years, while the individual and combined flats declined to 0.72 to 1.56 years, though each with different PBT.

The annual CO_2 reduction for the Ashti house model in the instance of adjusting the building parameters was 1.2 tonnes, reaching 4.3 tonnes when both the parameters were adjusted, and the traditional cooler was replaced with the dew point air conditioner. By only applying the interventions to the building fabrics, the annual CO_2 emissions could be reduced to somewhere in the range of 0.3 to 0.5 tonnes. However, when both adjusting the building fabrication and replacing the cooler with the indirect dew point evaporative system, the annual CO_2 reduction was found to reach 1 to 2.8 tonnes. For all 71-house projects that consist of 44,164 houses, and 24 apartment projects that consist of 18,631 flats, the predicted annual CO_2 reduction with the adjusted building fabrication and when simultaneously replacing the cooling system with the newly developed dew point cooler, could reach 223,996 tonnes.

Generally, to extend the application coverage area, and apply the changes to the old existing buildings or just replacing the existing conventional air conditioners with the dew point cooling system could save a large amount of energy in Erbil. The study covered only the new built projects, not the existing units that form the highest percentage of residential units in Erbil.

The amount of savings could be predicted by using Table 7-1; it could predict the required sizing of the dew point cooler if the conditioned floor area is known. The local authorities need to be involved to adopt the output of this study, to put a set of regulations for new building projects and set a strong restriction for using the inefficient conventional coolers.

7.2 Conclusion

All objectives of the study are fully addressed and satisfied; after undertaking a wide literature review about the building fabrications and existence cooling systems in Kurdistan, two typical buildings were selected for the energy-saving study. These two case study models have been investigated by modelling software, to examine the effect of different building fabrication parameters on the cooling load and energy consumption. The optimum parameters were identified for the buildings to minimize the cooling load as much as possible. For further energy saving, the newly developed dew point evaporative cooler has been investigated to replace the conventional split air-conditioner. The physical size and annual water consumption of the cooler for both case studied were identified.

Economic and environmental analysis was conducted, covering the capital cost, operational cost, Pay Back Time (PBT) and annual CO_2 reduction. These investigations were carried out for both case studies; firstly with just adjustment of the fabrications, and secondly with the fabrication adjustments and replacing the split air conditioner with the dew point cooler, then compare them with the base cases. The benefit of the study was illustrated in terms of the energy and cost savings, and CO_2 reduction in larger scale to cover all investment building projects in Erbil. It determined that with the adjustment of the building fabrications and replacing the cooling systems, the energy savings for all newly built residential units could reach 23,462.048 MWh, which could solve the power issues in the city, and annual CO_2 could reach 223,996 tonnes.

A guideline that has never previously been produced in Kurdistan was formed in the study, which benefits the homeowners and designers. It predicts the energy and water consumption for cooling buildings. Additionally, it assumes the energy savings in the buildings with the optimum fabrication parameters or retrofitting the existing buildings, as well as the energy savings in case of replacing the conventional split conditioner with the dew point cooler. Table 7-1 shows the guideline reference for designing the residential building for energy saving purposes.

Table 7-1: Guideline reference for energy-saving and design in residential buildings in Kurdistan

Annual energy needs per model, kWh/m² floor area				
Energy	**House**	**Saving %**	**Flat**	**Saving %**
Electricity/conditioned air	41.3	0	33	0
With building intervention	30.47	26.2	15.1	54.2
Only dew point cooling	5.15	87.5	4.12	87.5
Dew point+ building intervention	3.8	90.8	1.89	94.3
Heat Exchanger Sizing/ m² floor area				
Base model m^3/m^2	0.02093		0.0165	
Optimum m^3/m^2	0.01499		0.0124	
Annual water consumption, m^3/m^2 floor area				
Base model	0.778		0.4028	
Optimum	0.57		0.3092	

The financial impact of this study is very clear in several sectors of the community. The first beneficiary is the homeowner, due to the small payback time if the old system replaced with the new dew point cooler, healthier indoor conditions. It also makes new opportunities for businesses for both construction and air-conditioning fields, as the study minimizes the energy consumption and guarantees the supply of cooling in the hot summertime.

7.3 Challenges to Replacing the Split Air Conditioner with the Dew Point Air Conditioner

Technical challenges related to the dew point cooler application in Kurdistan are not expected, but the possibility could well arise in terms of marketing this new system. As has been discussed, the system is expensive in comparison to traditional air conditioners, and consumers have greater trust in available, applied and guaranteed products, and will not risk the purchase of equipment that has not previously been in use or seen. In terms of providing such new systems to customers, suppliers will be extremely careful about investing their capital in new and expensive products, including such extra expenses as an advertisement and staff training, as well as the expectation of low sales at the beginning for an unpredictable period. As the system is quite bulky, and if it is installed in a building as one central unit it will require some duct fittings to deliver the conditioned air to the required zones, and some houses or building owners may not want to install ducts in their buildings for cosmetic reasons or due to the extra expense, especially in inhabited buildings.

7.4 Contribution to Knowledge

There is a lack of energy-related studies about Kurdistan. Building energy is one of the areas that has never previously been studied in this detail in this region. Studying building fabrications in Kurdistan and their effects on energy consumption for cooling is new, as buildings are built without any standards or by taking into consideration the relation between building fabrication and energy savings associated with cooling. Two main buildings have been selected from a large number of buildings that represent typical constructions; several building fabrications were tested, after which optimum parameters were found for each of the two building types and the effect of the applied interventions on the energy and cooling load determined.

Despite a growing number of published studies about indirect evaporative dew point cooling systems over the last few years, the system has never been introduced or used in Kurdistan. To investigate the feasibility of the system in Kurdistan, real weather data was applied and used in a simulation to estimate the size and the water consumption of the heat and mass exchanger based on the buildings' cooling loads, and on the effect of varying the building fabrication parameters on the cooler. The methodology used to combine the hourly cooling loads with the hourly output of the dew point cooler to size its heat exchanger is new. This resulted in limiting the size of the cooler and choosing the best outputs for the hot and dry climate generally so that it could be applied for different areas with the same climate conditions. The study is diverse research that normally needs a team to be carried out as it covers many areas such as building fabrics, modelling and simulations, then coupling them to form one rigid study.

7.5 Generalising and Impact of the Study

The results and the method of this study could be generalised and used for most areas of Iraq. The majority areas of the country have a similar climate to Erbil (hot/dry). The main cities in the Northern Iraq including cities of (Mosul, Kirkuk, Salahuddin and Duhok) have very similar climate to Erbil, but it gets hotter towards the South of the country. The building typology overall Iraq including Kurdistan is exactly same. The derived design guidelines for sizing the heat exchanger of case study 1 is 0.02093 m^3/m^2 and water consumption of 0.778 m^3/m^2 based on floor area, this could be applied to buildings in Iraq with similar weather condition (hot/dry).

The method could be used for similar climates such as Arizona and Nevada in the USA, taking into consideration the building typology difference, so the simulation needs to be modified depending on the difference between Erbil's case and the new case. Then, the simulation could be used for any input parameters (weather condition), then predicts the water consumption and cooling output of the dew point cooler for that particular climate, subsequently combines the building load required to estimate the final size and water consumption for design purposes.

Additionally, the outcomes of this research work will help develop a robust methodology that can be used potentially for other regions with similar climates and other demographic cohorts.

7.6 Recommendations for Further Research

Further studies are required to develop a standard building code for Iraq, applications and barriers to adopting any new requirements demanded by the government in terms of the construction, as well as an investigation into the implementation processes in terms of their social acceptance. The building code could be imported from developed countries such as the USA, where similar climates can exist, but it should be investigated in more detail, similar to the Al-Istidama construction code in Dubai.

Due to the importance of preserving energy, additional research is necessary for the field of indirect evaporative cooling, especially in terms of installation of the system into different buildings, such as offices, schools and hospitals. Further investigation is required to analyse indoor air quality and comfort temperature ranges in different buildings, should the need for energy savings becomes a requirement. This is because this study showed that increasing indoor temperature within occupants' comfort levels could save significant capital costs and energy expenditure.

Dew point evaporative cooling system has the potential to replace the traditional air conditioners for better air quality, energy consumption. The system performance reduced at high ambient relative humidity, which is the constraint or a negative point of this system to use in places with high humidity ratio. Applying desiccant systems to the dew point cooler will widen and lifts the restrictions ceiling and enables the system to be used for different weather and climatic locations.

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APPENDICES

Appendix A: Kurdistan residential projects

City	Project name	Unit type	Units No	Design land m2	Actual building-Area m^2	Project land m2	Total Footprint/total Land
Erbil Governorate projects	Sardam	Villa	73	330	15899.4	105000	15.10%
	Marina 1	Villa	144	336	31933.44	87000	36.70%
	Marina 2	Villa	136	336	30159.36	87000	34.70%
	Marina 3	Villa	164	356	38533.44	87000	44.30%
	Talar city	House	680	231	94248	337500	27.90%
	Florya city	Villa	50	1000	33000	50000	66.00%
	Zilan city	House	460	180	49680	137500	36.10%
	Zhiyani New	House	138	300	24840	50000	49.70%
	Ganjan city	House	1400	300	252000	4046860	6.20%
	Ganjan city	Villa	1000	600	396000	4046860	9.80%
	Lawan city	Villa	1150	205	155595	500000	31.10%
	Warin	Villa	650	450	193050	875000	22.10%
	Warin Flat	Flat	155	160	24800	875000	2.80%
	Al Manara -average	House	1400	230	193200	662500	29.20%
	Ashti city 1	**House**	**1900**	**237**	**270180**	**999574**	27.00%
	Ashti city 2	**House**	**2700**	**252**	**449064**	**999574**	**44.90%**
	Ashti jewel	Villa	120	400	31680	81230	39.00%
	Global city	Villa	1700	300	336600	1051875	32.00%
	Zin city- average- (large project)	Villa	1024	487	398950.4	510000	78.20%

	Zerin city	Villa	Details not given	300	-	592000	-
	Dashti bahasht	House	450	273	81081	175000	46.30%
	Dashti bahasht	Flat	1216	115	139840	175000	79.90%
	Lana city	House	464	200	55680	214000	26.00%
	Lana city	Villa	55	300	10890	214000	5.10%
	Lana city- 10 floor	Flat	200	175	35000	36000	97.20%
	Park view- averaged Flat	Flat	982	263	258266	50000	516.50%
	New Iskan Flat	Flat	2520	150	378000	150000	252.00%
	Jihan city apartments	Flat	1404	308	432432	99000	436.80%
	Harshem city	House	500	200	60000	360170	16.70%
	Green land	Villa	500	2500	475000	2023000	23.50%
	Green land	Flat	360	125	45000		-
	Naz city	Flat	700	225	157500	181000	87.00%
	Zhian city	House	226	200	29832	130200	22.90%
	Zhian city	Flat	496	130	64480	19800	325.70%
	Safiran city	Villa	90	460	36018	112500	32.00%
	Hewa city	Villa	500	233	101355	-	-
	Hewa city	Flat	3000	180	540000	-	-
	Asuda city	Flat	520	180	93600	-	-
	Bafrin city	Flat	192	160	30720	-	-
	Bafrin city	Villa	-	-	-	-	-
	The Atlantic	Flat	1080	184	198720	362250	54.90%
	The Atlantic	Villa	480	200	63360	362250	17.50%
	Korean city	House	1000	200	120000	398000	30.20%
	Hamoon city -koya	House	289	300	52020	645000	8.10%
	4 towers	Flat	320	196	80000	10000	800.00%
	Erbil housing- project	Flat	504	135	68040	-	-

Erbil housi- project 2	Flat	504	135	68040	-	-
Golden City	Villa	40	400	10560	29000	36.40%
Nawroz City	Flat	480	125	60000	85000	70.60%
Shahan city	Flat	672	127	85344	-	-
Shahan city	House	220	200	26400	-	-
White land- aver	Flat	480	125	60000	39600	151.50%
AL ZAITOON	Villa	2000	250	500000	2100000	23.80%
4 TOWERS	Flat	298	193	57514	7500	766.90%
Koya City	Villa	450	220	65340	125000	52.30%
Ayinda city	Villa	-	216	0	402500	0.00%
New azadi	Villa	500	-	-	747500	0.00%
Aram city	House	-	-	0	250000	0.00%
New life	Flat	504	120	60480	37500	161.30%
Harsham city	House	500	210	63000	222425	28.30%
Sari blind	House	-	-	0	250000	0.00%
Pank village	Villa	297	300	71280	165000	43.20%
Kurdistan city	Villa	-	-	0	197500	0.00%
Future city	Flat	768	-	0	670000	0.00%
Future city	Villa	309	-	0	670000	0.00%
Dahati new	Villa	510	220	74052	250000	29.60%
American village- Khanzad	Villa	300	500	99000	317500	31.20%
Lebanees village	Flat	1100	143	157300	240000	65.50%
Lebanees village	Villa	140	450	55440	240000	23.10%
Awnay Shar	House	1000	171	102600	375000	27.30%
Heja Flat	**Flat**	**176**	**140**	**24640**	**18490**	**133.30%**

Suleymaniyah Governorate projects	Sardam	House	300	180	32400	105000	30.90%
	Helen city	House	116	230	16008	50000	32.00%
	Ranya	House	1000	230	138000	500000	27.60%
	Ranya - rozh city	House	1873	250	309045	1000000	30.90%
	Diya city	Villa	301	220	43705.2	205000	21.30%
	Diya city	Flat	364	135	49140	205000	24.00%
	Green city	Villa	500	300	99000	175000	56.60%
	Charmo city-chamchamal	Villa	289	250	43350	645000	6.70%
	Danya city	Flat	828	-	-	97300	-
	Danya city	Villa	26	-	-	97300	-
	Daik projerct	Villa	40	-	-	150000	-
	Daik projerct	Flat	360	-	-	150000	-
	Birwa city	House	75	-	-	-	-
	Goran city-halabja	House	1000	200	120000	85000	141.20%
	Rozh city	Villa	1873	235	290502.3	1000000	29.10%
	Barez city	House	620	240	89280	175000	51.00%
	Lubnan city	House	396	200	47520	110000	43.20%
	Ranya city - ranya	House	1000	200	120000	204475	58.70%
	Dashti bahasht	Villa	300	-	-	-	-
	Kurd city 1- aver	Flat	960	90	86400	175000	49.40%
	Kurd city 2	Flat	624	100	62400	207000	30.10%
	German village	Villa	104	777	56565.6	404686	14.00%
	German village	Flat	320	183	58560	404686	14.50%
	Gouyza aparments	Flat	432	160	69120	176038	39.30%
	Sulemania heights	Villa	911	300	180378	1250000	14.40%

	Sulemania heights	Flat	1089	150	163350	1250000	13.10%
	Qaiwan city-aver	Villa	358	230	54344.4	95000	57.20%
	Qaiwan city-aver	Flat	320	120	38400	95000	40.40%
	New Halabja	House	502	-	-	-	-
	Barzanja	House	150	-	-	-	-
	Qaradagh	House	150	-	-	-	-
	Tabin town	House	500	-	--	-	-
	Raparin and Charmak	House	1000	-	-	-	-
	Goolajo	House	600	-	-	-	-
Duhok governorate projects	Hamoon city	House	105	200	12600	-	-
	Warvin	House	500	200	60000	364217	16.50%
	City Star	Flat	280	150	42000	1250000	3.40%
	City Star	Villa	870	250	143550	1250000	11.50%
	Avro city	Flat	3912	161	629832	999574	63.00%
	Kayar Group Flats	Flat	660	120	7800	-	-
	Zeriland	Flat	-	-	-	-	-
	Aram City	Flat	1120	135	151200	130000	116%

Appendix B: Indirect evaporative cooling systems study

No	Researcher	Type of flow	Plate thickness mm	Length mm	Width mm	Height-No channels	Channel mm	Air velocity	Air ratio Work/supply	Plate material	Effect	
1	Peng Xu [182] experiment	Counter flow vertical plate	0.1-0.3	1000	358	0.80 m	-	750 m3/hr	0.44 0.36 Optimum	Al and Coolmax fibre	WB% Dew % COP	1.14 0.75 52.5
2	X. Cui [183] Math model experiment	Counter vertical	-	750	300	-	10 prim 6 sec	1.5 m/s	0.3	-	WB% Dew % COP	1.01-1.06 - -
3	J. Lin [168] Sim modelling	Counter flow Vertical	-	1000	100		5	2 m/s	0.33	-	WB% Dew % COP	1.0 - -
4	X. Cui [184] Analytical sim	Counter flow Vertical	0.5	1000	1 m	1 m	5				WB% Dew % COP	
5	Z DUAN [101]	Counter flow vertical	0.3	1200	NA		10 mm	0.5-2.4	0.5	Aluminium foil-textile fibre	WB% Dew % EER COP	0.55 1.10 0.40-0.85 7.8-34.1 3-12

6	Kumar[123]	Counter-flow-vertical	0.5	1200	80		5	2.4	0.33	Cotton sheets-polyurethane	WB% Dew % COP	0.92-1.14 0.58-0.84 -
7	Demis [114] numerical	Counter flow Vertical	0.5	700	500		3	3	0.5	-	WB% Dew % COP	
8	X. cui [185]	Counter flow - vertical		750	300		Prim 10 Sec 6	1.5	-	-	WB% Dew % COP	
9	J. Lin [168]	Counter flow - vertical	-	1000	100		5	2	0.3	-	WB% Dew % COP	1-1.06
10	J. Lin [186]	Counter flow	-	1000	100	-	5	2	0.33		WB% Dew % COP	1.06 072.
11	Demis Pandelidis [113]	Counter flow		700	500	-	3	3	0.5	-	-	
12	Demis Pandelidis [116]	Counter flow	-	500	500	-	3	3	0.3		-	-

13	Zhiyin Duan [102]	Counter flow 0.2	0.25	900	314	-	6	1.58-2.83	0.5	0.25	WB% Dew % EER	0.79-0.91 0.14- 1.13 2.8-15.5
14	Sheng Huang [187]	Counter flow vertical	0.1	765	565	190 24 channels	3.95	-				
15	A.E Kabeel [188]	Counter flow -tables	0.4	1000	750	300	6			Aluminium layers		
16	Shhab Moshari [189]	-	0.3	690	550	350	Dry-20 Wet-10	1				
17	J Lin [190]	Counter	0.25	600	150	4.5	5	1.5 m/s 0.9-2.3	0.5	Polymer cellulose		
18	Stefano [191]	Counter vertical	0.14	470	470	119	3.21	-		Aluminium alloy with surface dimples		
19	Guangya Zhu [192]	-	0.3	500			Dry-10 Wet-5	1				
20	Peng Xu [193]	vertical	0.1-0.3 coolmax	1000	358	800	3	750m3/hr	0.44 Recommended (0.365)	Coolmax fabric	WB% Dew % COP	 1.02-1.14 52.5

21	Ali Shohani [194]			1800	1800	2500	>3mm	2.5		Fibre glass HX plate		
22	Z Duan [19]	Vertical counter flow	0.25	900	314		6			Cellulose aluminium foil		
23	Kumar [111]	Vertical counter flow	0.5	1200	80		5	2.4	0.33	Cotton sheet-polyurethane	WB% Dew % COP	0.92-1.14 0.58-0.84
24	X Zhao [107]	Cross flow	0.24	1200	-	35 sheets	4	150m3/hr	0.34	Polyethylene		
25	Z Duan [109]	Counter flow – system model		860	458	320 channels	3 mm	3.6	0.47 0.44 best	Plastic and cellulose fibre	WB% kW EER	0.96-1.0 5.7-7.3 13.2-17.1
26	Kashif Shahzad [195]	Cross flow 0.1	0.3	900	280	480	5	450cfm				

Appendix C: IEC simulation of dew point (code)

```
clc
clear all
close all
%Outdoor temperature
OT = xlsread('.xlsx')';
%Outdoor relative humidity
Q = xlsread('.xlsx')';
%Number of cells (one dry channel + one wet channel)
Num=;
%Mass flow through dry channel
M=0.0/Num;
%Length of cooler
LLL=00;
%Width of cooler
ZZZ=00;
%Height of cooler
HEIGHT=0.11;
%Thickness of sheet
LS=0.02;
%Thickness of water
LW=0.000;
%Thermal conductivity of sheet
KS=1;
%Thermal conductivity of water
KW=0.0;
%Thermal conductivity of air
KA=0.0260;
%Air ratio (mass flow in wet channel/dry channel)
X=1;

% Element size
DELTA_L=0.5;

% Error1 belongs to calculation inlet air parameters
error1=0.000000;

% Error2 belongs to calculation outlet air parameters
error2=0.0000001;

% Number of Elements
N_E=LL/DELTA_L;
```

```
OT=OT';
RH=Q';
N=size(OT,1);
N=1;

for p=1:N
disp(['--------------------']);
disp(['Hour' num2str(p)]);
TD=OT(p,1);
TD0=TD;
Q=RH(p,1)/100;
P=101325;
CP=1.006;
TWA=LS+LW;
KON=TWA*KS*KW/(LS*KW+LW*KS);

for j=1:N_E
disp(['Number of iteration=' num2str(j)]);
X_HB(p,j)=j*DELTA_L/LL; %Dimensionless length

T_OUT=TD;

kk1 = 6.5459673*log(T_OUT+273.15)/log(2.718281828);
kk2 = -0.000000014452093*((T_OUT+273.15)^3);
kk3 = 0.000041764768*((T_OUT+273.15)^2);
kk4 = -0.048640239*(T_OUT+273.15);
kk5 = 1.3914993-5800.22/(T_OUT+273.15);
K = kk1 + kk2+ kk3+ kk4+ kk5 ;
PWS=exp(K);
WS=0.621945*PWS/(P-PWS);
M=Q/(1+(((1-Q)*WS)/0.621945));
W=M*WS;
W0=W;
PW=(P*W)/(0.621945+W);
TDB=6.54+14.526*(log(0.001*PW)/log(2.718281828))+0.7389*(((log(0.001
*PW)/log(2.718281828))^2))+0.09486*(((log(0.001*PW)/log(2.718281828)
)^3))+0.4569*(((0.001*PW)^0.1984));
PWWS=0.99*PWS;
C = 1;
while abs(C)>error1
      PWWS=PWWS-error1*0.1;
      WSS=0.621945*PWWS/(P-PWWS);
      TWB=(2501*WSS-T_OUT-2501*W-1.867*W*T_OUT)/(2.381*WSS-4.186*W-
1);
```

```
      KK=6.5459673*log(TWB+273.15)/log(2.718281828)-
0.000000014452093*((TWB+273.15)^3)+0.000041764768*((TWB+273.15)^2)-
0.048640239*(TWB+273.15)+1.3914993-5800.22/(TWB+273.15);
      FPWWS=exp(KK);
      C=PWWS-FPWWS;
end
disp(['RelativeHumidity=' num2str(Q)])
disp(['OutSide Temperature=' num2str(T_OUT)])
disp(['DewPoint Temperature=' num2str(TDB)])
disp(['WetBulb Temperature=' num2str(TWB)])

H=(CP*T_OUT+W*(2501+1.867*T_OUT));
HS=(CP*T_OUT+WS*(2501+1.867*T_OUT));

if(j==1)
    T=T_OUT-error2*10;
else
    T=T_HB(p,j-1)-error2*10;
end
DIFF=1.0;
i=0;

while abs(DIFF)>error2;
      i=i+1;
      KF1= 6.5459673*log(T+273.15)/log(2.718281828);
      KF2= -0.000000014452093*((T+273.15)^3);
      KF3= 0.000041764768*((T+273.15)^2);
      KF4= -0.048640239*(T+273.15);
      KF5= 1.3914993-5800.22/(T+273.15);
      KF=KF1+KF2+KF3+KF4+KF5;
      PWSF=exp(KF);
      WSF=0.621945*PWSF/(P-PWSF);
      HF=(CP*T+W*(2501+1.867*T));
      HFS=(CP*T+WSF*(2501+1.867*T));
      A=(HS-HFS)/(T_OUT-T);
      CC=X*MF;
      CH=MF*CP/A;
      CMIN=min(CH,CC);
      CMAX=max(CC,CH);
      CR=CMIN/CMAX;
      %Hydrolic diameter
      HD=(2*(ZZ*HEIGHT)/(ZZ+HEIGHT));
      %Convective heat transfer coefficient in dry and wet channels
      CHT=5.3*KA/HD;
      BETA=CHT/(CP*1000);
      %Overal heat transfer coefficient (U-value)
      US=1/CHT+TWA/KON;
```

```
        CEF=A*US*1000+1/BETA;
        U=1/CEF;
        S=ZZ*j*DELTA_L;
        NTU=U*S/CMIN;
        EPSIL=(1-exp(-NTU*(1-CR)))/(1-(CR*exp(-NTU*(1-CR))));
        EPSILR=(CH*(HS-HFS))/(CMIN*(HS-HF));
        QWR=EPSIL*CMIN*(HS-HF);
        QWT=MF*CP*(T_OUT-T);
        T_NEW=T_OUT-(QWR/(MF*CP));
        DIFF=T_NEW-T;
        T=T_NEW;
end

S_E=ZZ*DELTA_L;
if(j==1)
    d_QWT=MF*CP*(T_OUT-T);
else
    d_QWT=MF*CP*(T_HB(p,j-1)-T);
end

WFT=T-(d_QWT*1000*US/S_E);

disp(['Dimensionless Length=' num2str(X_HB(j))]);
disp(['ProductAir Temperature=' num2str(T)]);
disp(['Water film Temperature=' num2str(WFT)]);

T_HB(p,j)=T;
WFT_HB(p,j)=WFT;
QWT_HB(p,j)=d_QWT*1000/S_E;
HS_HB(p,j)=HF;
end
COEFF=BETA*S_E/(X*MF);
for j=(N_E):-1:1
    if(j==N_E)
        WWFO_HB(p,j)=W;
    else
        WWFO_HB(p,j)=WWFO_HB(p,j+1);
    end
    WWFO=WWFO_HB(p,j);
    kk11=6.5459673*log(WFT_HB(p,j)+273.15)/log(2.718281828);
    kk22=-0.0014452093*((WFT_HB(p,j)+273.15)^3);
    kk33=0.0041764768*((WFT_HB(p,j)+273.15)^2);
    kk44=-0.048640239*(WFT_HB(p,j)+273.15);
    kk55=1.3914993-5800.22/(WFT_HB(p,j)+273.15);
    KFF=kk11+kk22+kk33;
    PWSW=exp(KFF);
    WSFO=0.621945*PWSW/(P-PWSW);
```

```
    WSFO_HB(p,j)=WSFO;
    WWFO=((1-0.5*COEFF)*WWFO_HB(p,j)+COEFF*WSFO)/(1+0.5*COEFF);
    WWFO_HB(p,j)=WWFO;
    if(j==N_E)
        HF_I(p,j)=HF;
    else
        HF_I(p,j)=(QWT_HB(p,j)*S_E/1000)/(X*MF)+HF_I(p,j+1);
    end

    %Water consumption (L)
    WC(p,1)=Num*(WWFO_HB(p,1)-W0)*X*MF*3.6*1000;

    %Cooling capacity (KW)
    QCC(p,1)=Num*(1-X)*MF*CP*(TD0-T_HB(p,N_E));

    %Fan power
    mio=0.00001; %Dynamic viscosity of humid air
    r=1.185;
    epsd=0.9;
    epsw=0.6;

FanPower=((32*mio*LL*(MF/(r*ZZ*HEIGHT))/(HD^2))+(epsd*0.5*r*((MF/(r*
ZZ*HEIGHT))^2)))*MF+((32*mio*LL*(X*MF/(r*ZZ*HEIGHT))/(HD^2))+(epsw*0
.5*r*((X*MF/(r*ZZ*HEIGHT))^2)))*X*MF;
    TFO(p,1)=Num*FanPower;

    WAT_HB(p,j)=(HF_I(p,j)-2501*WWFO)/(CP+1.867*WWFO);

    disp(['Dimensionless Length=' num2str(X_HB(p,j))]);
    disp(['Air humidity ratio in wet channel='
num2str(WWFO_HB(p,j))]);
    disp(['Air Enthalpy=' num2str(HF_I(p,j))]);
    disp(['Working Air Temperature=' num2str(WAT_HB(p,j))]);

end

end
```

Appendix D: Ethics approval

Amita Patel

From: Amita Patel
Sent: 12 March 2013 17:13
To: Research Students; Ivan Korolija
Cc: Anne Smith; 'P04178546@myemail.dmu.ac.uk'
Subject: FW: Ethics Application 1213/166 - Mahmud Mustafa P04178546

Hello

Please see Bernd's email below approving this ethics application.

Kind regards
Amita

From: Bernd Carsten STAHL [mailto:bstahl@dmu.ac.uk]
Sent: 11 March 2013 21:09
To: Amita Patel
Cc: Anne Smith; P04178546@dmu.ac.uk
Subject: RE: Ethics Application 1213/166 - Mahmud Mustafa P04178546

I can approve this application by Chair's action. It does not need to be reviewed by the FHREC.
Kind regards,
Bernd

From: Amita Patel [mailto:a.patel@dmu.ac.uk]
Sent: 11 March 2013 16:20
To: Bernd Stahl
Cc: Anne Smith; P04178546@dmu.ac.uk
Subject: Ethics Application 1213/166 - Mahmud Mustafa P04178546

Hello Bernd

Attached is a new ethical application for you to consider.

Kind regards
Amita

Amita Patel

Faculty Secretary/Administrator
Faculty of Technology

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